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Fuzed Insensitive General Purpose Bomb Containing AFX-645 - Final Report

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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13. ABSTRACT *(Maximum 200 words)*

An insensitive high explosive based on TNT, NTO, wax and Aluminum called AFX-645 has been developed for general purpose bombs. This IHE has undergone a series of reformulations over the past four years to improve its processability, control sensitivity and enhance blast performance. Sub-scale and full scale testing in a Mk-82 bomb has been accomplished. Performance measurements including detonation velocity, blast pressure, copper cylinder expansion and fragment velocity indicate performance comparible to Tritonal. Sensitivity testing of the previously developed AFX-644 formulations including friction, impact, thermal stability, electrostatic discharge, cap, gap, Susan, friability, fast -cook-off, slow cook-off, bullet impact and sympathetic detonation tests have been accomplished. The explosive has passed the United Nation's Extremely Insensitive Detonating Substance test criteria in its baseline AFX-644 formulation. A subsequent less sensitive formulation has passed the most critical of the article tests for the 1.6 hazard classification.

Extensive boostering test were done and a complete explosive train to detonate AFX-645 has been designed. This explosive train fits into a slightly modified FMU-139 fuze with a large auxilliary booster stored in a new fuzewell. Minor modifications to the Mk-82 were embodied to incorporate the new fuzewell and explosive train. When installed as a nose or tail fuze in an AFX-645 filled Mk-82, the weapon should meet 1.2 hazard classification criteria.

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PREFACE

This program was conducted by Mr. John Corley, of the Armament Directorate, Energetic Materials Branch (WL/MNME), Captain (CAF) Dennis J. Desprey and his successor Captain (CAF) Alan Stewart of the Armament Directorate, Fuzes Branch (WL/MNMF). The program was conceived as a technology demonstration program integrating what appeared to be relatively mature technologies. The objective of the program was the weaponization of an insensitive high explosive for general purpose bombs. During the course of the investigation, it was determined that significant alterations of TNTO IV (later called AFX-644) were required to achieve a reproducible, qualifiable explosive fill (designated AFX-645). Modifications to the Mk-82 bomb and the FMU-139 fuze were demonstrated, completing the demonstration program. Testing showed the feasibility of fielding a 500 lb. general purpose bomb which can be stored and transported as an 1.6 Hazard Classification ordnance package. In a fuzed state the weapon passed fast cook-off and sympathetic detonation tests making it a candidate for 1.2 Hazard Classification.

ACKNOWLEDGMENTS

The authors wish to express their extreme gratitude to the following individuals and agencies:

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Mr. Phil Lett for scheduling (and re-scheduling again and again) the range resources needed for the large number of full scale tests conducted during the program.

Mr. Derrick Hinton from 46 TW for making sense out of a lot of confusing blast pressure data from tests conducted over a considerable time and with varying instrumentation set-ups.

The highly professional technician teams at ranges C-64A, C-80 and B-75 for their outstanding cooperation, flexibility and dedication not to mention the overtime just before Christmas.

Capt (CAF) Jim Desprey for conducting most of the booster development work and much of the fuze design of this program.

Mr. Art Spencer and the WL/MNME explosive processing team for their outstanding loading support and contributions to improve processing of AFX-644 and its modifications.

Mr. Fred Bath of WL/MNMF for assistance in assembling and transporting fuze components throughout the program.

Lt. Jon Ratz and Lt. Brad Noland for their studies to characterize AFX-644 modifications with various wax/surfactant systems.

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Fuzed Insensitive General Purpose Bomb Containing AFX-645

Section One: Introduction

The U.S. Air Force Wright Laboratory, Armament Directorate recently completed an in-house technology demonstration program. The program objective was to develop a general purpose bomb which can be stored as an Insensitive Munition (IM). The system developed integrates a modified FMU-139 fuze and a modified Mk-82 (500 lb.) bomb containing the insensitive high explosive AFX-645. Goals of the program include demonstration of a fuzed bomb which achieves 1.2 hazard classification and a non-fuzed bomb which achieves 1.6 hazard classification while maintaining the lethality of tritonal. These goals were realized recently in full-scale testing using prototype hardware in the Fuzed, Insensitive, General Purpose Bomb (FIGPB) program.

Wright Laboratory has developed an insensitive high explosive for general purpose bombs, designated AFX-645, which is readily initiated by a modified version of the FMU-139. AFX-645 is a qualifiable insensitive high explosive bomb fill. Explosive performance is approximately 95% that of tritonal. Fully assembled, fuzed bombs can be safely stored and transported using this explosive fill. This paper discusses improvements to baseline AFX-644 which led to the development of AFX-645. The results of an extensive series of performance and safety tests are documented as well as the initiation experiments to produce a viable explosive train. The paper also details the FMU-139 fuze and Mk-82 bomb modifications required to achieve a Fuzed, Insensitive, General Purpose Bomb (FIGPB).

1.1 Background

The technologies developed for this program were a high priority during the Cold War when the USAF required a high degree of readiness for conventional warfare in Europe. The system of centralized munitions depots, with quantity/distance (Q/D) restrictions associated with hazard class/division 1.1 munitions, limited transportation and storage of explosives at the main operating bases. The inability to preposition ordnance was viewed as a major operational deficiency. At many installations, storage igloos designed to hold 250,000 lbs. of munitions contained only a small fraction of that capacity.

Benefits associated with reducing the hazard classification of munitions systems can be quantified in terms of reduced separation distances and/or increased utilization of available storage volumes as illustrated in Table I. Tests and criteria for achieving hazard classification 1.2 and 1.6 of explosive filled articles are provided in Table II from Reference 2.

Table I: Storage Advantages for Hazard Classification 1.2, 1.6 Munitions Systems (Example: Storage Igloo with capacity of 300,000 lb. HE)[1]

Safety Hazard Classification	1.1	1.2	1.6
Distance to Inhabited Building @ Igloo Load of:	3620 Feet with 60,000 lb. (20 %)	800 Feet with 240,000 lb. (80 %)	195 Feet with 300,000 lb. (100 %)

USAF interest in insensitive munitions declined with the reduced emphasis in combat in the European theater. US Navy interest remains high due their unique storage requirements aboard ships and aircraft carriers. Should future conflict require storage of munitions in a theater which mandates the use of munitions which meet the United Nations safety criteria, the technologies have been developed. The Gulf war brought to the forefront other issues such as time and labor constraints associated with bomb build-up. These issues are also addressed with insensitive munition concepts as they lend themselves to all-up-round (AUR) ordnance packages which can be stored and shipped as pre-assembled units. Technology developed in this program would allow future bombs to be stored fully assembled, closer to delivery platforms. This eliminates the cumbersome last-minute build-up of munitions during wartime operations, reduces time-consuming transportation of the munitions and makes them less vulnerable to attack.

Insensitive munitions require the employment of less sensitive explosives and explosive formulations. The Los Alamos National Laboratory (LANL) has demonstrated that 3-nitro-1,2,4-triazol-5-one (NTO) possesses both insensitivity and high energy[18]. NTO is an off-white, crystalline solid particulate explosive that decomposes at 270°C to 278°C and has no stable low melt point. NTO is easily synthesized from two low cost ingredients, formic acid and semicarbazide (aminourea), to form the intermediary 1,2,4-triazol-5-one (TO). TO can then be nitrated in 70% nitric acid at 50 to 60°C to produce NTO. Yields are favorable in both steps, from 80 to 90 percent. NTO has favorable performance performance properties. Its detonation velocity is 8.2 mm/μsec. at a density of 1.85 g/cm^3. The impact sensitivity of NTO is 291 cm using a 2.5 kg weight (type 12 tool). Therefore, NTO represents an attractive candidate as a base to form an insensitive composite explosive.

Melt cast systems are the most suitable for loading large quantities of items, an essential need with general purpose bombs due to their high demand and large size. Therefore a suitable melt cast binder is necessary to process the solid particulate NTO. Such a melt cast formulation will utilize existing Army Loading-Assemble-Packing facilities, which have the capacity to fulfill general purpose bomb requirements. TNT is most suitable as that melt castable binder since it has a stable low melt, thermal stability, and a long history of use in such applications. TNT and NTO, designated TNTO when combined, provides a slurry when heated, which can be cast into warheads[3]. Additives such as particulate aluminum and desensitizing wax can then be added to obtain the desired level of sensitivity and energy output.

Two reformulation efforts were undertaken using TNTO IV (baseline AFX-644) as a starting point. The first effort sought to replace the low melt wax (D2) and the nitrocellulous surfactant. The product of this work was AFX-644 Mod 0 which was an extremely insensitive yet poor performing explosive. The performance parameters of this formulation were enhanced in the second reformulation effort by increasing the percentage of energetic ingredients to as high as possible and still pass insensitivity tests.

The insensitive high explosive developed during this program, AFX-645, is easily processed in existing melt/cast, Load-Assemble-Pack facilities such as those at McAlester Army Ammunition Plant (MCAAP) in McAlester, OK. Furthermore, a domestic production source has been developed for nitrotriazolone (NTO), the explosive ingredient which gives the formulation its unique combination of insensitivity and high performance. A standardization agreement (STANAG) specification for NTO is being drafted among the nations of the North Atlantic Treaty Organization (NATO).

1.2 Layout of Report

The program was originally planned to be a relatively short technology demonstration of several 'nearly mature' technologies. It was believed at the beginning of the program that TNTO IV (baseline AFX-644) explosive (a mixture of TNT and NTO), a modified FMU-139 and a slightly redesigned Mk-82 bomb could be easily integrated into an ordnance package which could achieve the insensitive munition criteria. As the program progressed, it became apparent that considerable reformulation work was required for TNTO IV. Also, numerous iterations of boosting schemes were tried and a plethora of performance and sensitivity tests were required. The span of work reported here is approximately four years.

This report is organized to assist the reader in understanding the logic of decisions made throughout the program. The tests are not explained in chronological order. Section Two of the report will explain the development, characterization and testing of TNTO IV, the baseline AFX-644 formulation. The first reformulation effort will be explained in Section Three. Numerous processing parameters were altered and the result on sensitivity will be explained. Although the formulation percentages for AFX-644 Mod 0 were identical to those for baseline AFX-644, AFX-644 Mod 0 was less sensitive and yielded lower performance parameters. A second reformulation effort was undertaken to trade some of the extra insensitivity of AFX-644 Mod 0 for performance. This second reformulation yielded the final product of the investigation, an insensitive high explosive which uses the same ingredients as AFX-644 Mod 0 but in different quantities. This final product has been designated AFX-645. Much of the discussion and conclusions relating to AFX-644 are equally applicable to AFX-645. Section Four explains the second reformulation as well as the performance tests for both reformulation efforts. Section Five covers the booster and fuze hardware configuration designs which spanned the entire program and were tested against a variety of AFX-644 formulations. Section Six covers the full scale hazards testing of the fuzed bombs which were the final proof of the viability of the concepts demonstrated in this program. The report wraps up with a list of well substantiated conclusions.

Section Two: Baseline AFX-644 Formulation Characterization and Evaluation

The development of the baseline AFX-644 (also referred to as TNTO IV) insensitive high explosive is detailed in Reference 3. AFX-644 is a melt-castable, wax-desensitized, nitrotriazolone (NTO)-based explosive formulation which employs TNT as an energetic binder material and aluminum powder to enhance blast performance. TNT, NTO, Wax, and Al powder are mixed in proportions of 30, 40, 10 and 20%, respectively. Baseline AFX-644 meets the United Nations' (UN) criteria for Extremely Insensitive Detonating Substances (EIDS) and full scale testing requirements for fast cook-off, slow cook-off and bullet impact. Mixed results were obtained in full-scale sympathetic detonation testing with the baseline formulation. Mk-82 pressure arena tests for baseline AFX-644 yielded performance parameters similar to those obtained for tritonal-filled bombs.

Table II: Baseline AFX-644 Formulation Results[3]

Screening		
Test	**Criterion**	**Result**
Impact Sensitivity (H-50%, 5 Kg)		> 200.5 cm
Friction Sensitivity (BAM)		6.2 Kg
Thermal Stability (CRT)		0.37 cm^3/g
Electrostatic Discharge		0.040 Joules
Small Scale Burn (TNT/NTO/Wax 42/52/6)		Mild Burn
United Nations Criteria for Extremely Insensitive Detonating Substance (EIDS) for 1.6 Hazard Classification		
Test	**Criterion**	**Result**
Cap	No Detonation	No Reaction
Gap (Comp B Donor)	No Go @ 82 mm*	No Go @ 41 mm
Susan	Pressure < 27 kPa	Pressure = 17 kPa
Friability	dP/dt < 15 MPa/s	dP/dt = 0.3 MPa/s
Bullet Impact	No Explosion	No Reaction
External Fire	No Violent Reaction	Pressure Rupture
Slow Cook-off	No Fragment Throw	Deflagration
United Nations 1.2 and 1.6 Hazard Classification Article Tests in Mk-82 Bomb		
Test	**Criterion**	**Result**
Slow Cook-off	No Detonation (1.6)	Burn only (2X)
Fast Cook-off	No Detonation (1.6) No Mass Explosion (1.2)	Burn only
Bullet Impact	No Detonation (1.6)	Burn only (6X, 3 round bursts)
Sympathetic Detonation	No Propagation (1.2 and 1.6)	Adjacent: No Go (5X) @ 0.5 inches Diagonal: No Go (2X) @ 5.16 inches Go (2X) @ 5.16 inches

*Gap thickness criterion is a function of donor output pressure:
P(70mm, Pentolite)=P(82mm, Comp B)= P(76mm, RDX/Wax) = 34 Kbar.

Results of screening tests, EIDS tests and full scale (Mk-82) article sympathetic detonation and slow cook-off tests conducted for the baseline AFX-644 formulation have been reported previously[3] and are summarized here also in Table II. The results of additional slow cook-off, fast cook-off, bullet impact and sympathetic detonation tests are also provided in Table II and described in the text that follows. All tests in Table II describe the criteria for achieving 1.6 hazard classification with some exceptions. Screening tests have no hard criteria as they are intended for identification of promising formulations. The 1.2 hazard classification does not require the use of EIDS qualified explosives. The article testing for 1.2 hazard classification includes only the fast cook-off (with a relaxed pass criterion) and the sympathetic detonation test.

2.1 Baseline Slow Cook-off Testing

2.1.1 Baseline AFX-644 Slow Cook-Off Test 1

The first slow cook-off test on the baseline AFX-644 formulation was described in Reference 3. The item was placed in an aluminum oven equipped with thermocouples, controllable electrical heat tapes, exudation troughs, circulating air and insulation (Figure 1). The first slow cook-off test conducted on baseline AFX-644 in a standard Mk-82 bomb resulted in mild burning of the explosive contents with reaction products released upon rupture of the nose fuzewell. No case fragmentation was observed (Figure 2). The oven temperature at the time of reaction was 161° C, and the internal bomb temperature was 190° C.

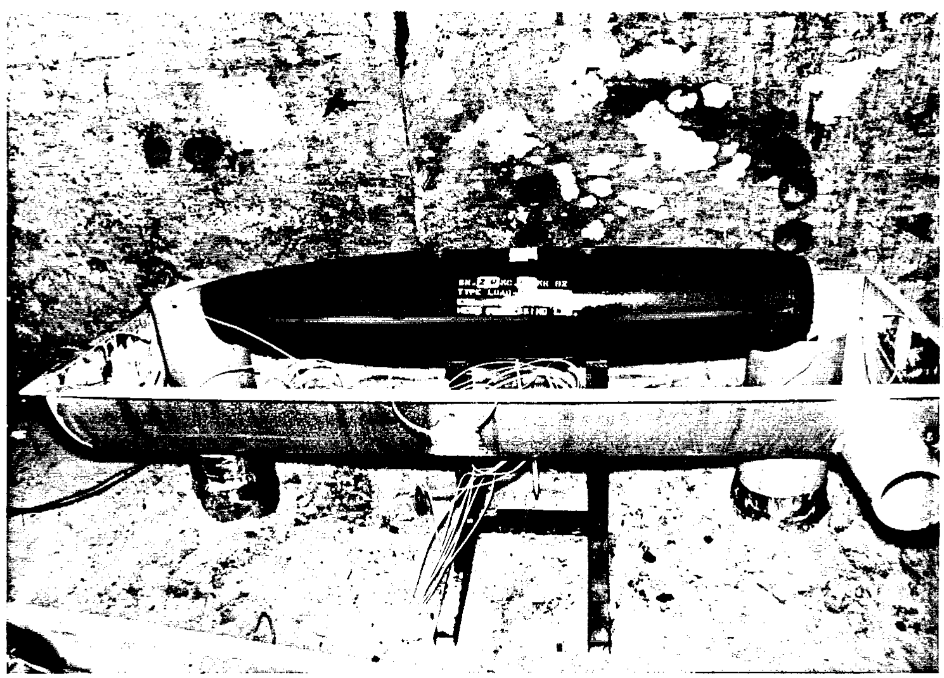

Figure 1: Slow Cook-off Test Set-Up

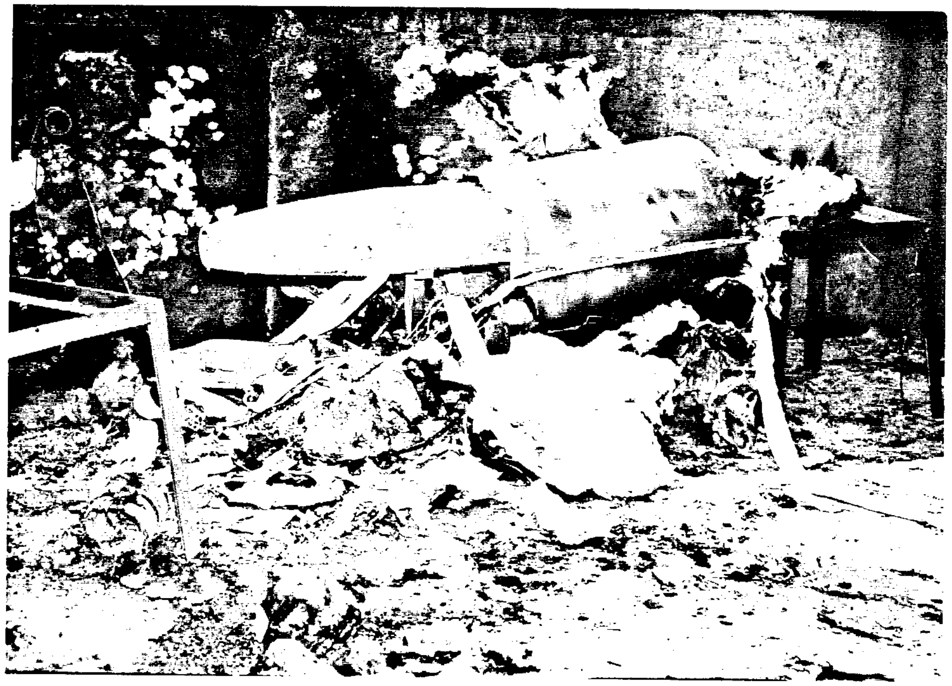

Figure 2: Baseline AFX-644 Slow Cook-off Test 1 Result

2.1.2 Baseline AFX-644 Slow Cook-off Test 2

A second Mk-82 slow cook-off test was conducted for the baseline AFX-644 formulation. As in the first test, the item vented mildly through the nose fuzewell and burned non-propulsively (Figure 3). The test item had thermocouples positioned in the bomb, on the bomb skin and in the oven free air. The oven temperature was initially raised from 28°C to 100°C at an approximate heating rate of 10.3°C/hr. The item was soaked at this condition for approximately 14.5 hours until equilibrium between the oven air temperature and the internal bomb temperature was achieved. The oven temperature was then raised at a rate of 3.3°C/hr to 140°C. At this point in the experiment, there was a power outage for approximately 8 hours. The oven cooled to approximately 40°C and the internal bomb temperatures decreased to as low as 74°C. Once power resumed, the oven air was heated to 100°C at a rate of 13.3°C/hr. It was again soaked at this condition for approximately 6.5 hours allowing the internal temperatures to equilibrate.

Heating then resumed at an approximate rate of 3.2°C/hr until reaction occurred at an oven air temperature of approximately 167°C and an internal item temperature near 190°C. Subsequently, fire ensued as molten explosive from the exudation troughs ignited. The item vented mildly from the nose and burned non-propulsively. The item fell from the stand during the test. It was noted prior to testing that the bomb was resting on the exudation troughs, suspended above the metal stand. The nose fuzewell was buried in ashes and residues making inspection difficult. The tail fuzewell was inverted at its base. “Tuff seal” exudation was observed about the tail ring. The bomb case remained intact throughout the experiment.

Figure 3: Baseline AFX-644 Slow Cook-off Test 2 Result

2.2 Baseline AFX-644 Fast Cook-off Test

A single item wood bonfire test was conducted for a Mk-82 containing the baseline AFX-644 formulation. The item was placed on the bottom section of a standard metal storage pallet. The pallet and item were strapped loosely to a steel frame stand (Figure 4). The item was surrounded by wooden planks (Figure 5) soaked with 15 gallons of diesel fuel and ignited using thermite grenades. Thermocouples were placed in and around the item to monitor the corresponding temperatures throughout the test.

The item vented mildly and burned in place approximately 10 minutes after the fire started. It remained on the stand for the duration of the test (Figure 6). Reaction occurred when the flame temperature was fluctuating between 1500°F and 2000°F. The internal thermocouples registered temperatures well below 1000°F prior to reaction indicating reaction initiated near the surface as would be expected in a fast cook-off scenario. Venting occurred from the nose first. Eventually, combustion products were emitted from the tail fuzewell and the charging well at the center of the bomb also. The positions of the thermocouples were similar to those of the slow cook-off tests.

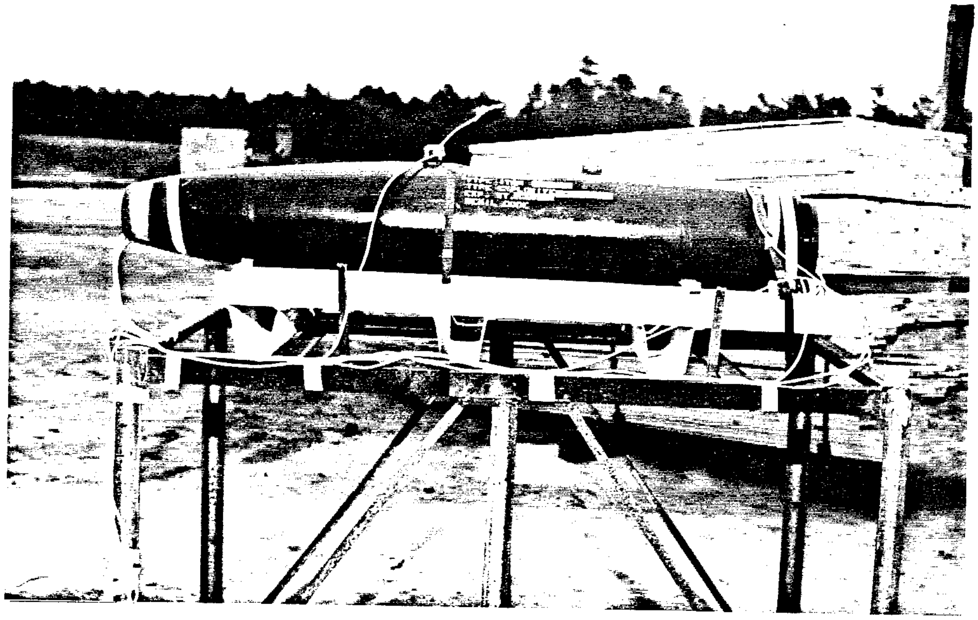

Figure 4: Wood Bonfire (Fast Cook-off) Test Set-Up

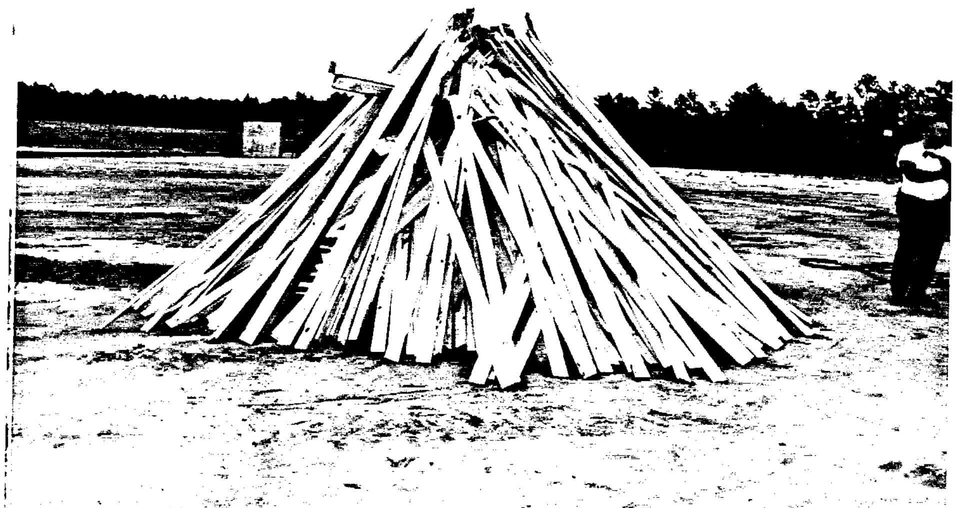

Figure 5: Wood Bonfire (Fast Cook-off) Test Before Ignition

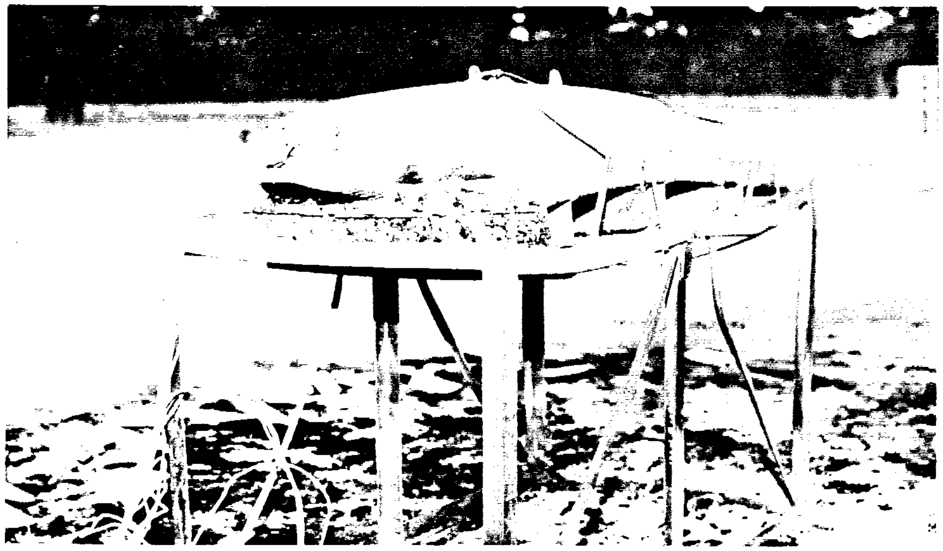
Figure 6: Baseline AFX-644 Fast Cook-off Result

2.3 Baseline AFX-644 Bullet Impact Tests

Two Mk-82 bombs containing baseline AFX-644 were subjected to bullet impact testing using 0.50 cal AP ammunition. The items were at a standoff distance of 60 feet from the muzzles of three Mann barrels (Figures 7,8). Each item was impacted with three separate three-round bursts delivered at service velocity with 100 millisecond intervals between rounds. Prior to firing into the live munition items, rounds from each Mann barrel were fired individually through light screens to obtain an average delivery velocity. The first light screen was placed approximately 10 feet from the barrel and was five feet in front of the second screen. The average velocities were 2947±33.9 ft/sec, 2954±26.4 ft/sec and 2932±15.0 ft/sec for barrels 1,2 and 3, respectively. No significant reaction or burning resulted from any of these impacts and the items remained intact.

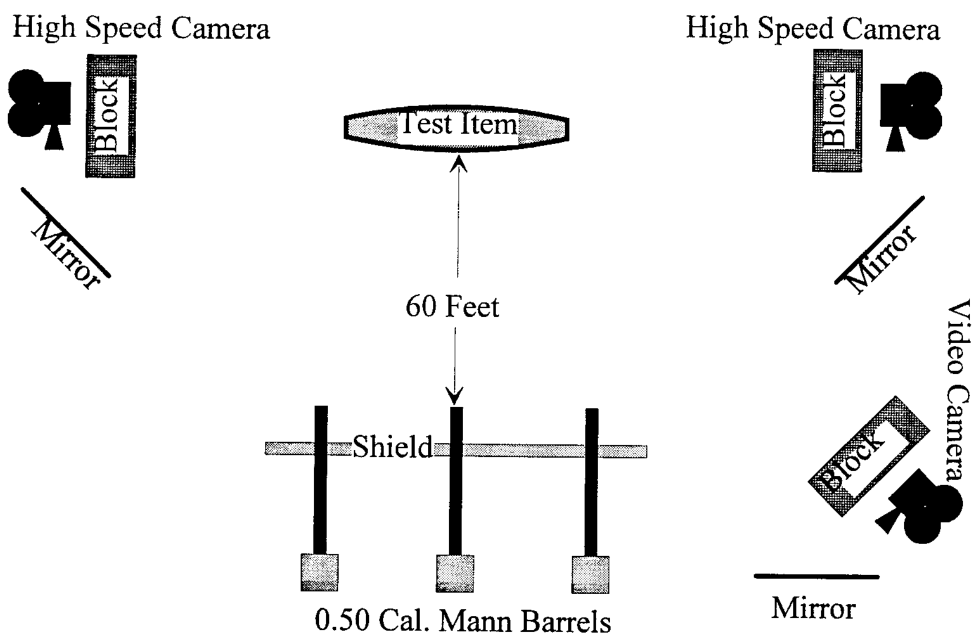

Figure 7: Schematic of Bullet Impact Test Set-Up

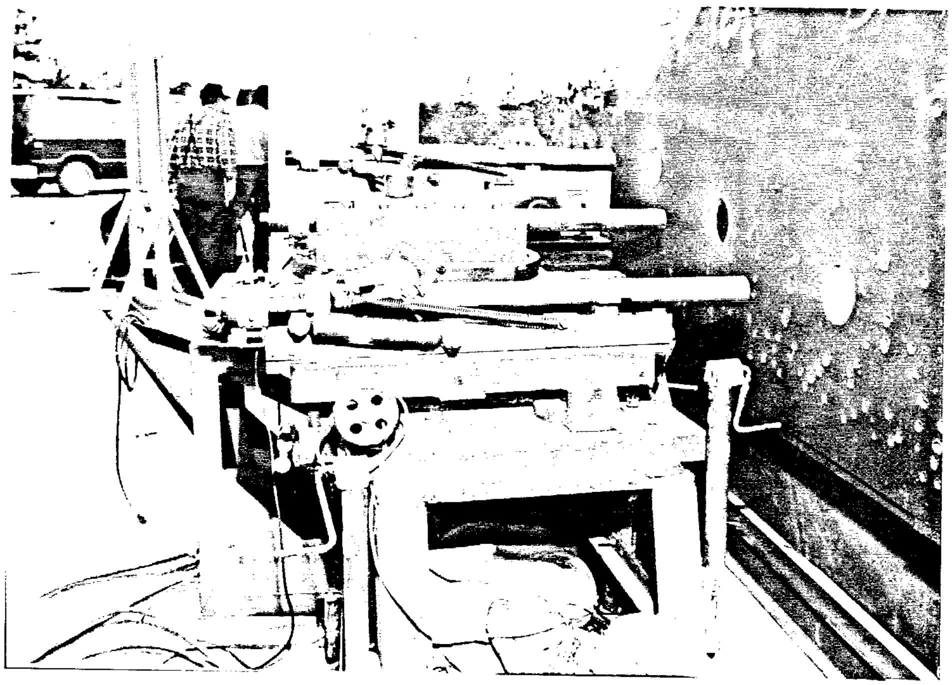

Figure 8: Mann Barrels Used for O.50 Cal Bullet Impact Testing

2.3.1 Bullet Impact Test--Item 1

The aim point for the first three round burst in the first item was the side of the bomb, orthogonal to and centered between the lugs. Two of the rounds completely penetrated the item and exited the backside of the bomb, displacing the internal explosive, creating a hole in the bomb. The impact holes were grouped closely together with the edges of the center hole contacting the other two holes. No significant burning was observed and the item remained completely intact (Figure 9).

The second three round burst in the first item was delivered along the same side of the item as the first but at a point ten inches in front of the forward lug. Again, the rounds entered the test item in a closely grouped pattern, with two of the entry holes overlapping and the third located approximately 1 inch from the cluster. None of these rounds exited the bomb case, but they did transverse the entire diameter of explosive as indicated by the slight case deformation on the backside of the test item. No reaction occurred from these impacts (Figures 9,10).

The third three round burst in the first item was delivered into the tail fuzewell. One round penetrated the fuzewell along the top edge. The second round penetrated the center of the fuzewell and the third entered through the bottom of the fuzewell. Again, no significant reaction was observed, although there was some mild smoking for a short time after the impacts (Figure 11).

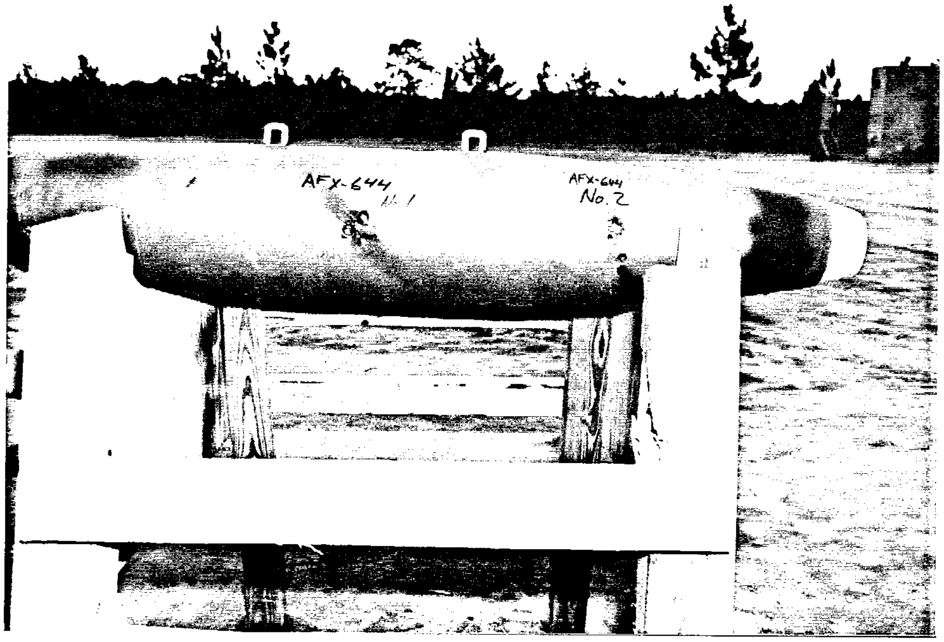

Figure 9: Baseline AFX-644 Bullet Impact, Item 1, Shots 1 and 2 Results

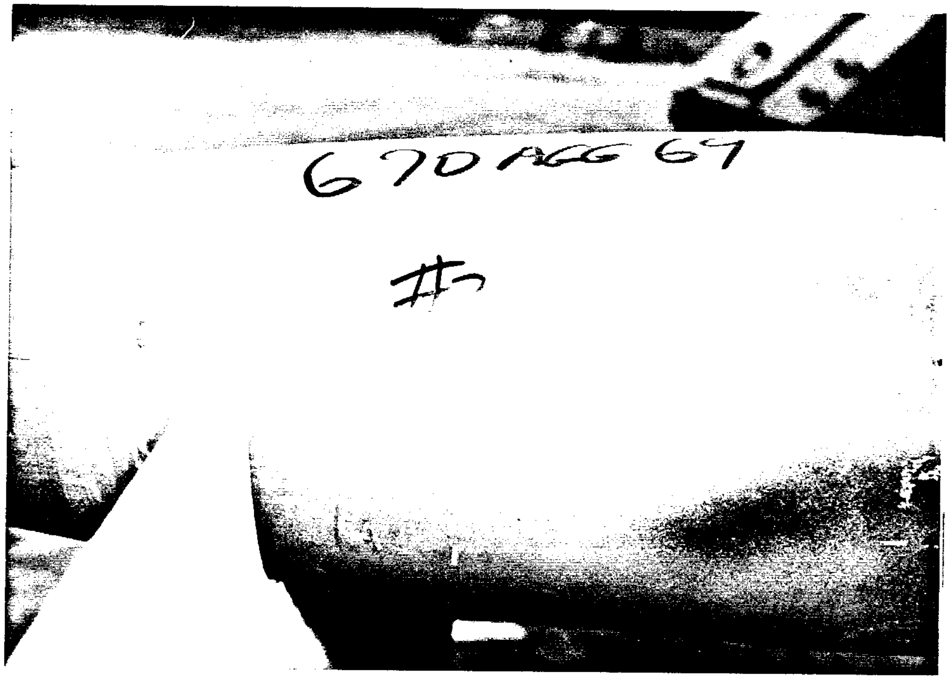

Figure 10: Baseline AFX-644 Bullet Impact, Item 1, Shot 2 Rear Side

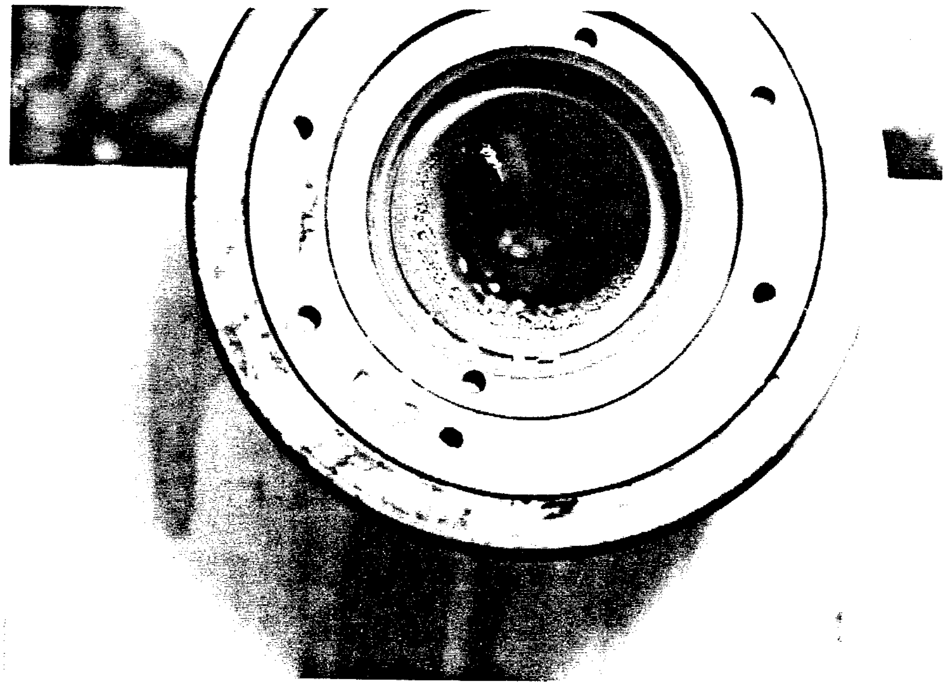

Figure 11: Baseline AFX-644 Bullet Impact, Item 1, Shot 3 Result

2.3.2 Bullet Impact Test--Item 2

The aim point for the first three round burst in the second item was, again, along the side at the center point between the lugs. Two of the rounds impacted closely together, resulting in over-lapping entry holes. The third round apparently tumbled upon exiting the barrel and impacted the test item approximately ten inches from the aim point. The penetration of this round resulted in an oblong hole. The bullets from these impacts became lodged into the test item and did not penetrate the item completely (Figure 12). The seal around the tail fuzewell was compromised from the pressure release and minor reaction induced by these impacts. The fuzewell was slightly crushed and tuffseal was observed exuding from the case. The nose fuzewell was slightly crimped and both nose and tail fuzewells were coated with explosive residue (Figure 13). Unreacted high explosive was visible in all of the impact holes. Most of the explosive charge appeared to be intact, so it was decided to continue testing with this item.

The aim point for the second three round burst into the second item was, again, in the side of the item at a point ten inches in front of the forward lug. Two of the rounds impacted the bomb case near the aim point, penetrating within two inches of each other. The third round impacted near the forward lug position in a glancing blow fashion, failing to penetrate the case wall. One of the two penetrating rounds exited the back of the bomb case (Figure 14). There was some mild smoking initially and more residue was observed in the nose fuzewell. Unreacted explosive was visible inside the bomb via the penetration holes. No significant reaction occurred and the charge remained essentially intact.

The third three round burst into the second test item was delivered into the nose fuzewell since the tail fuzewell had been compromised. Smoke exited the charging well and nose fuzewell when the bullets impacted. After the shot, unreacted, damaged explosive could be seen at the base of this fuzewell (Figure 15). No charging tube damage was observed.

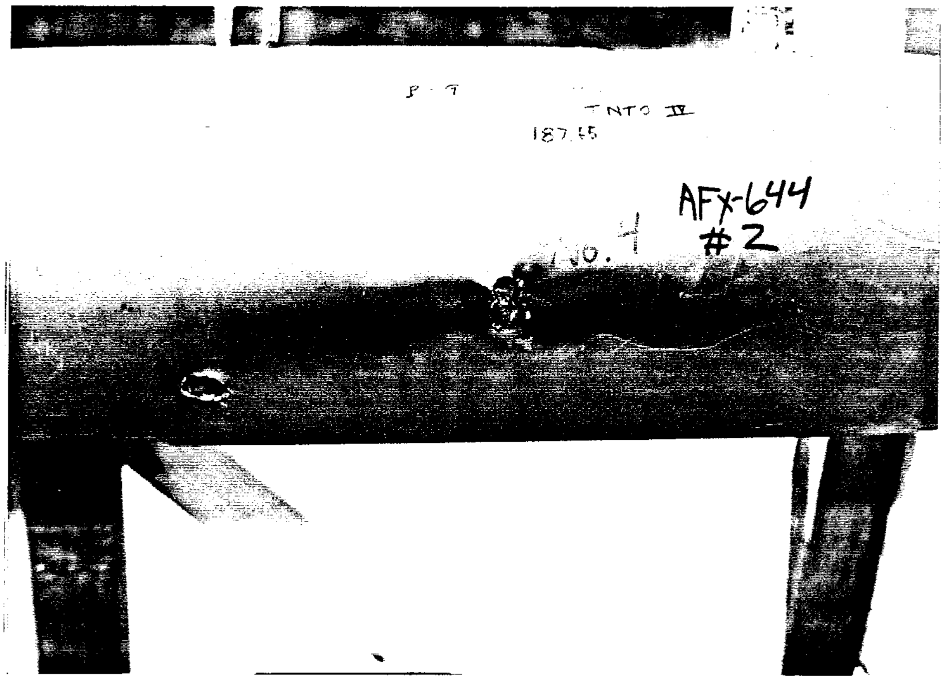

Figure 12: Baseline AFX-644 Bullet Impact, Item 2, Shot 1 Result

Figure 13: Baseline AFX-644 Bullet Impact, Item 2, Shot 1 Fuzewell Rupture

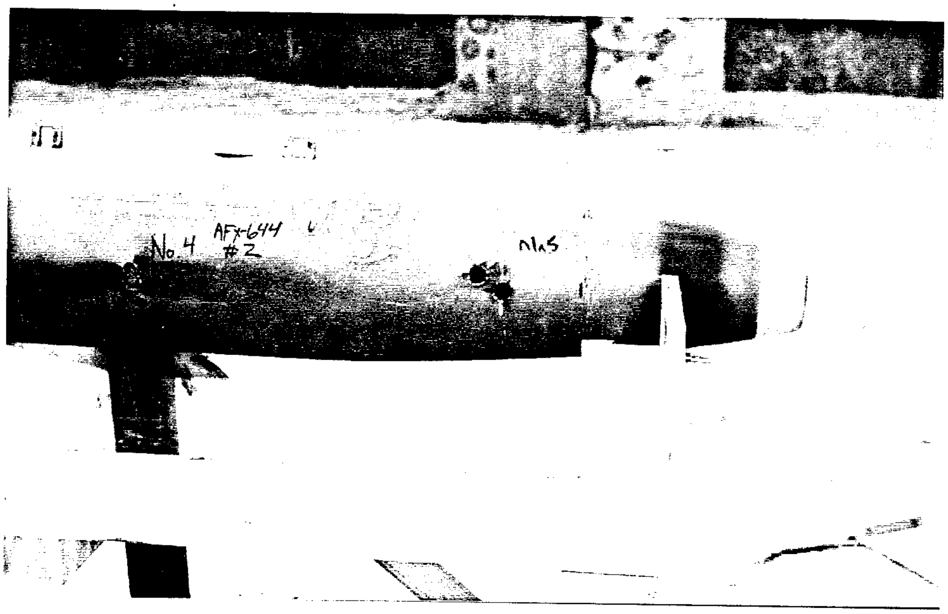

Figure 14: Baseline AFX-644 Bullet Impact, Item 2, Shot 2 Result

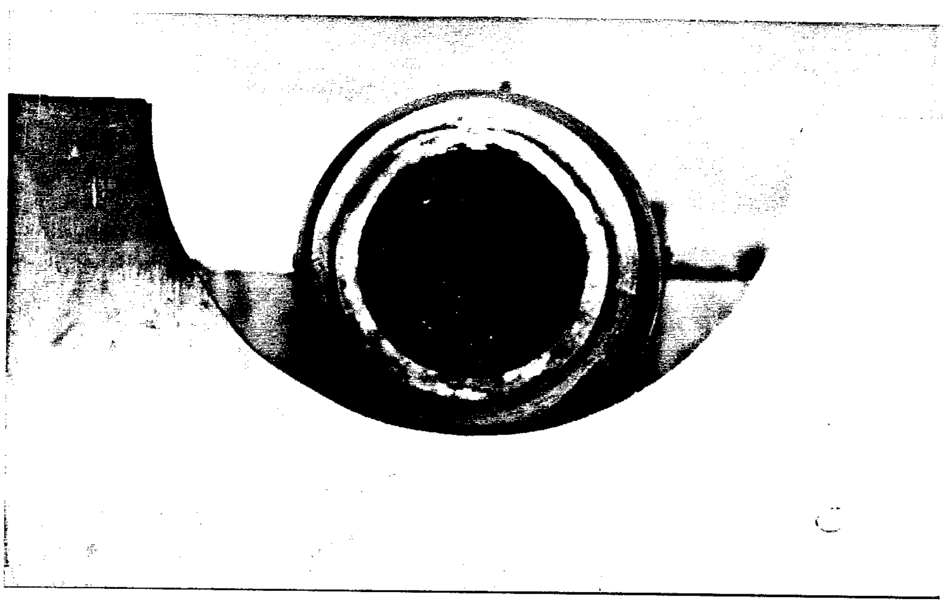

Figure 15: Baseline AFX-644 Bullet Impact, Item 2, Shot 3 Result

2.4 Baseline Sympathetic Detonation Tests

2.4.1 Baseline AFX-644 Sympathetic Detonation Test 1

The first full scale (MK-82) sympathetic detonation test on baseline AFX-644 was described in Reference 3. A summary description is presented here. The standard metal pallet contained three inert BDU-50s and three MK-82s containing baseline AFX-644. The old standard metal pallet which has vertical and horizontal skin-to-skin separation distances of approximately 0.5 inches was employed for the test (Figure 16). The donor bomb was located in the bottom row, center position of the pallet between a live acceptor bomb and a BDU-50. The top row of the pallet consisted of a BDU-50 between a live acceptor bomb and another BDU-50. The live acceptor bombs were on opposite sides of the pallet to allow individual assessment of the conditions at the adjacent and diagonal acceptor positions. The items were individually stamped for positive post test identification of the recovered remnants.

The loaded metal pallet was positioned above a 6 ft x 6 ft, 1-inch thick armored steel witness panel. A witness plate of the same dimensions was supported above the pallet on a wooden stand at a height of approximately 6 feet. A quantity of sand bags were placed on the top plate. Additional 6 ft x 12 ft, 1-inch thick panels were positioned on both sides of the pallet. The donor bomb was initiated from the nose using C-4 and an RP-83 boostered detonator (Figure 17).

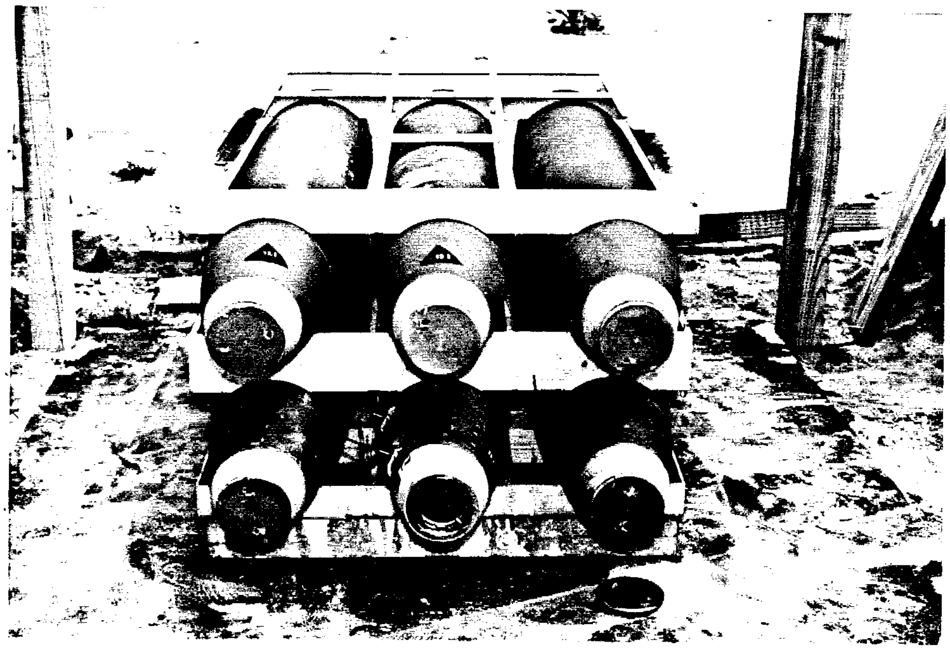

Figure 16: Old Standard Mk-82 Metal Pallet

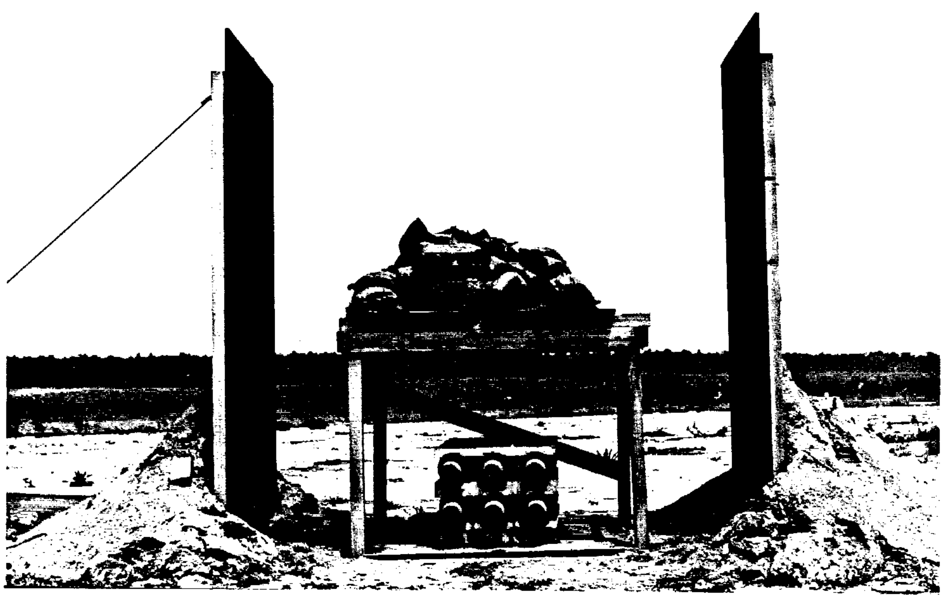

Figure 17: Sympathetic Detonation Test Set-Up

The detonation of the donor bomb did not propagate to either of the live acceptor bombs. The recovered pieces of the live diagonal acceptor bomb were large and plate-like. The charging well and lug well were also recovered form this item indicating this item did not detonate. The item was broken up severely from the jet-like impact of the donor fragments and its own subsequent low order reaction. The remnants of the adjacent live acceptor bomb also included heavy, plate-like pieces. Unreacted explosive was recovered from the arena. Evidence from the witness plates confirmed that no secondary detonation occurred.

2.4.2 Baseline AFX-644 Sympathetic Detonation Test 2

The second sympathetic detonation test on Mk-82s containing the baseline AFX-644 formulation also resulted in no propagation of the donor detonation. The set-up for the second sympathetic detonation test was the same as that of the first test. The donor bomb was nose initiated using C-4 and an RP-83 detonator. Piezoelectric pins were positioned at 5-inch intervals along the donor bomb to verify complete detonation of the donor bomb.

Portions of all test items were recovered along with the pin data and witness plate markings. The data confirmed prompt detonation of the donor bomb with no propagation to the surrounding items. The donor bomb promptly transitioned to an average measured detonation velocity of 7.01 $\pm$0.45 km/sec. The bottom witness plate was cracked and severely scarred by donor fragments. The markings were symmetrical about the center of the plate, with no markings from the acceptor items (Figure 18). The side panels were clean except for some minor markings from donor fragments (Figures 19,20). The top plate was deformed from impact by the top, center item and mildly scarred by donor fragments (Figure 21). Large, plate-like pieces with liner material still attached were recovered from the live adjacent item (Figure 22). Two small, thick pieces of the live, top row acceptor were recovered (Figure 23). The remaining inert items were broken apart and showed evidence of severe donor impacts.

Figure 18: Bottom Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 2

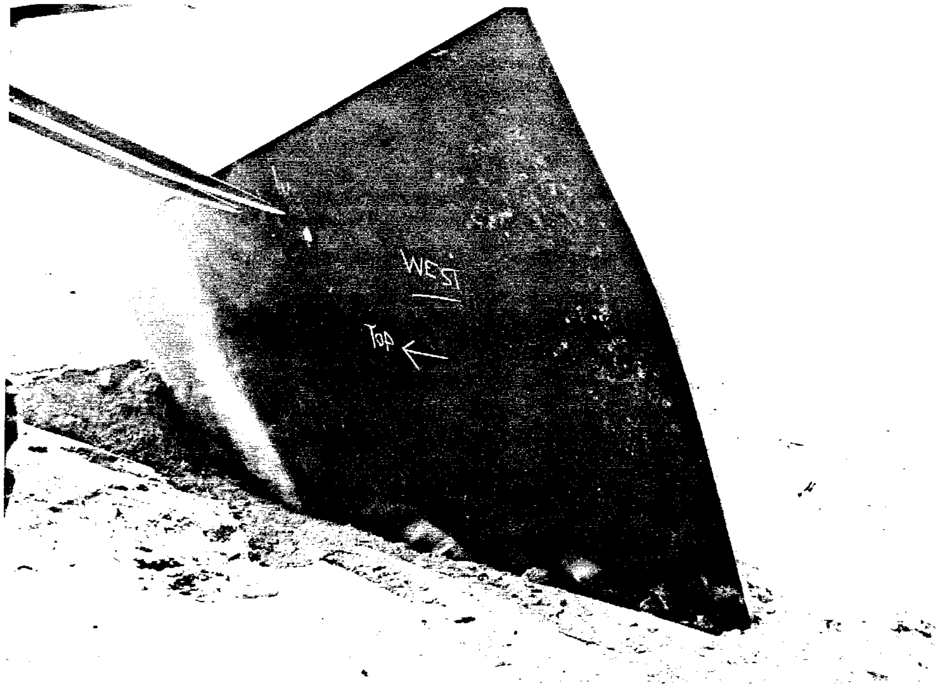

Figure 19: Live Adjacent Acceptor Side Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 2

Figure 20: Live Diagonal Acceptor Side Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 2

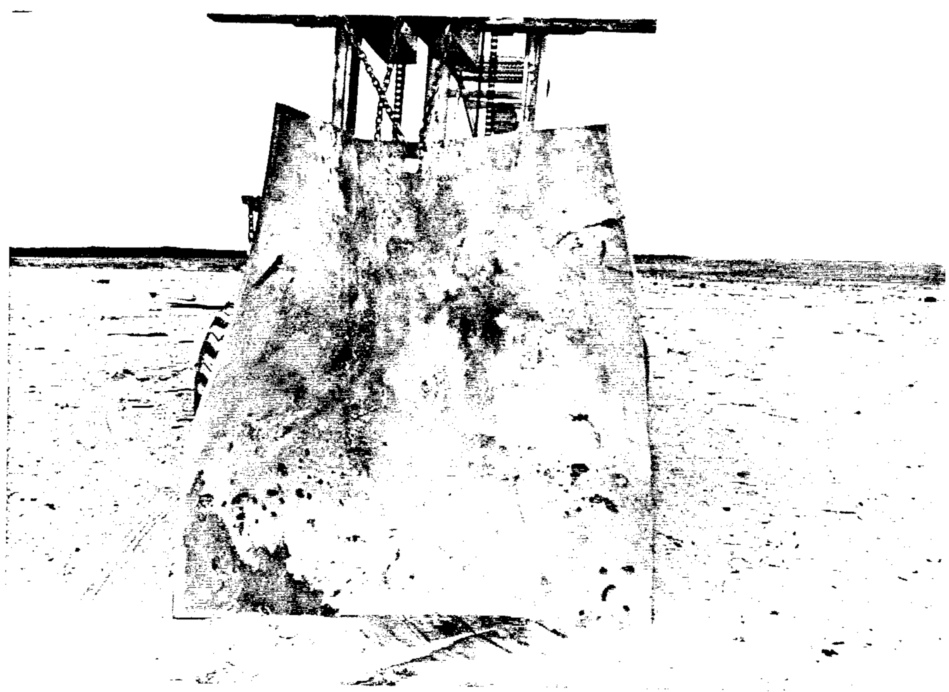

Figure 21: Top Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 2

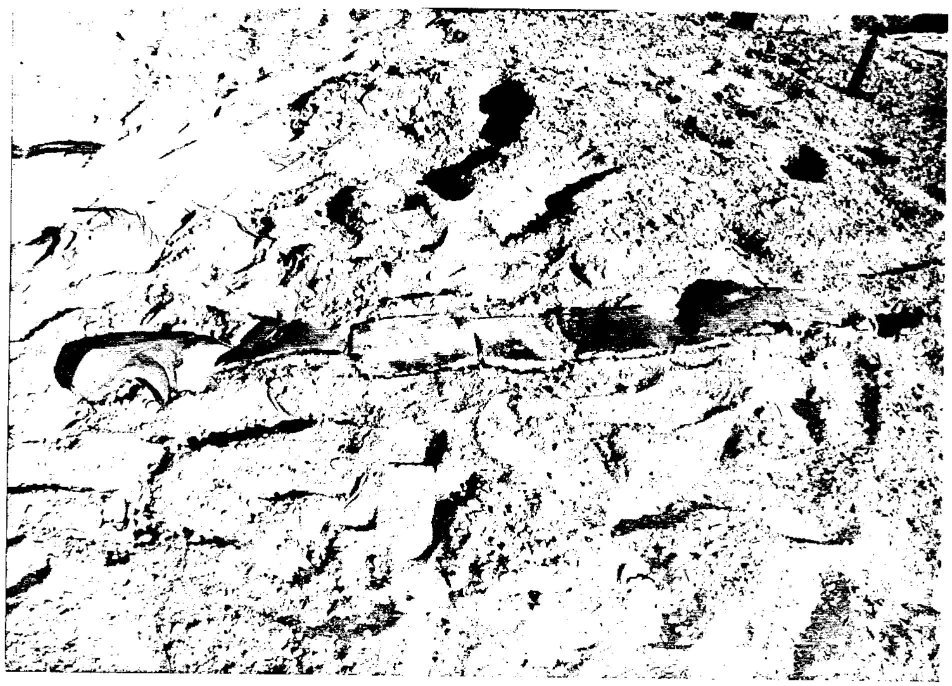

Figure 22: Live Adjacent Acceptor Remnant from Baseline AFX-644 Sympathetic Detonation Test 2

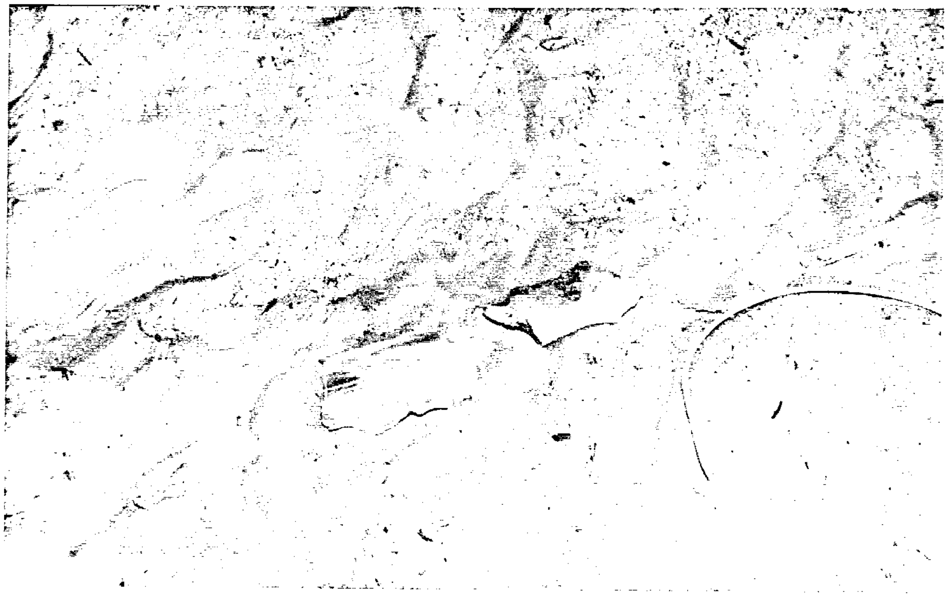

Figure 23: Live Diagonal Acceptor Remnant from Baseline AFX-644 Sympathetic Detonation Test 2

2.4.3 Baseline AFX-644 Sympathetic Detonation Test 3

At this point in the program, Mk-82 loading of baseline AFX-644 was transitioned to the Naval Ordnance Station Detachment (NOSDET) at Yorktown, Virginia. The transition was made to validate scale-up of the baseline formulation processing parameters (Eglin's 100 gallon melt kettle was not yet activated) and to expedite loading of large numbers of test items. Explosive weights for the 12 bombs loaded at Yorktown were lower than for any of the charges loaded previously at Eglin (183 $\pm$ 0.38 lbs. versus 188.8 $\pm$ 1.5 lbs.). The bombs loaded at Yorktown were not water-weighed prior to explosive loading. Using the average volume obtained for the bombs loaded at Eglin, the average charge density of the bombs loaded at Yorktown is estimated to have been 1.61 g/cm^3 versus 1.66 g/cm^3 for the bombs loaded at Eglin. A compositional analysis was performed at Yorktown on a single sample collected near the end of the mix. The 100 gallon kettles at Yorktown empty from the bottom, so this sample was from the "head" of the batch. The sample was rich in wax and deficient in aluminum, indicating some settling may have occurred. This may have resulted in wax deficient bombs loaded first with increasingly wax rich bombs produced thereafter. Samples were not collected prior to loading and the order of loading was not recorded. It is possible that bombs of varying energies and sensitivity levels were loaded, but it is impossible to assign these levels to individual bombs. This was discovered prior to testing the items. The decision was made to proceed with additional sympathetic detonation testing.

The next experiment in the test plan was an all live, Mk-82 sympathetic detonation test in the old standard metal pallet with 0.5 inches of separation between all adjacent items using bombs loaded at Yorktown. The test set-up was identical to that of the previous sympathetic detonation test with the exception that all acceptor bombs contained baseline AFX-644. The donor bomb detonated, achieving a detonation velocity of 6.42 $\pm$0.38 km/sec. The detonation of the donor bomb did not propagate to either of the acceptor bombs adjacent to the donor on the bottom row of the pallet as evidenced by the large plate-like remnants recovered from these items (Figures 24,25) and the absence of witness markings from these items on the bottom plate (Figure 26). The two acceptor bombs originally in the diagonal positions of the pallet propagated the donor detonation as indicated by the multiple fragment markings and penetrations on the upper portion of the vertical witness plates (Figures 27,28). The evidence regarding the top center acceptor is inconclusive but tends to indicate no detonation of this item. No positively identifiable pieces of this item were recovered. The top witness panel was heavily riddled with holes and impacts from the diagonal acceptor bombs (Figure 29). Additionally, there were some very fine fragment impacts in the center section of the top plate. It is speculated these are from small donor fragments which were able to circumvent the unreacting top center bomb body prior to its initial movement.

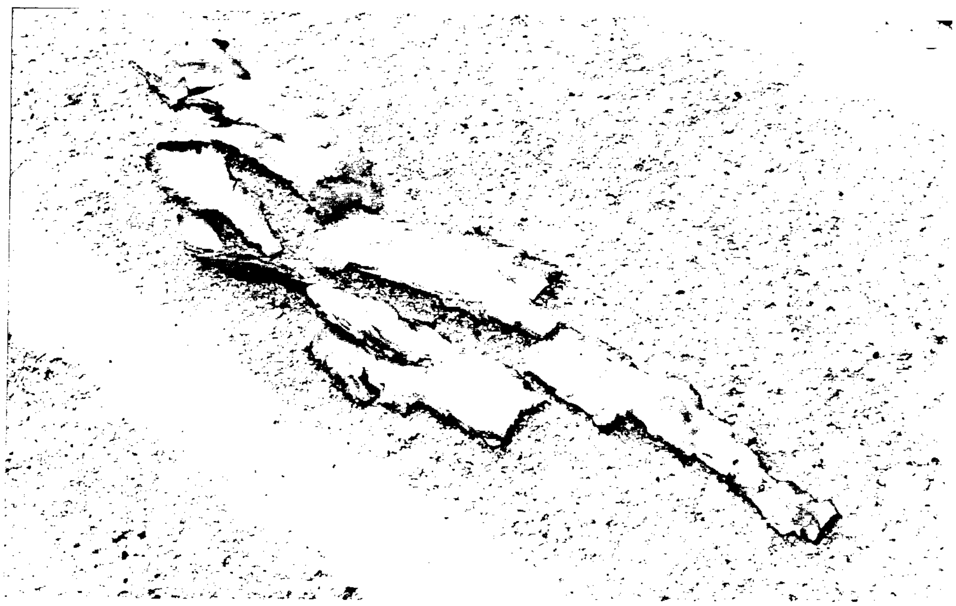

Figure 24: Live Adjacent Acceptor Remnant from Baseline AFX-644 Sympathetic Detonation Test 3

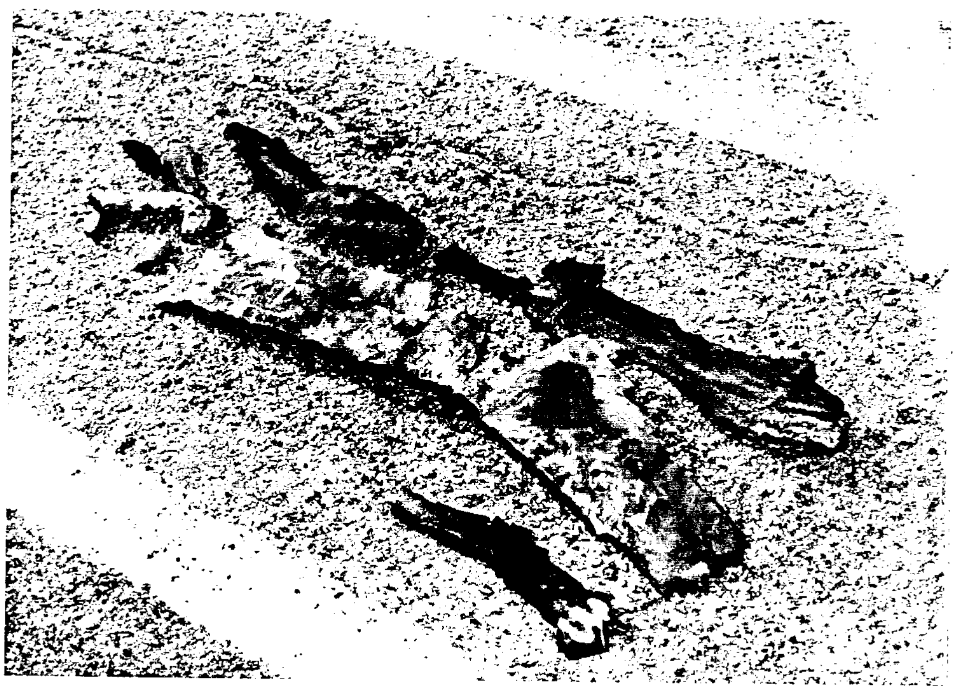

Figure 25: Live Adjacent Acceptor Remnant from Baseline AFX-644 Sympathetic Detonation Test 3

Figure 26: Bottom Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 3

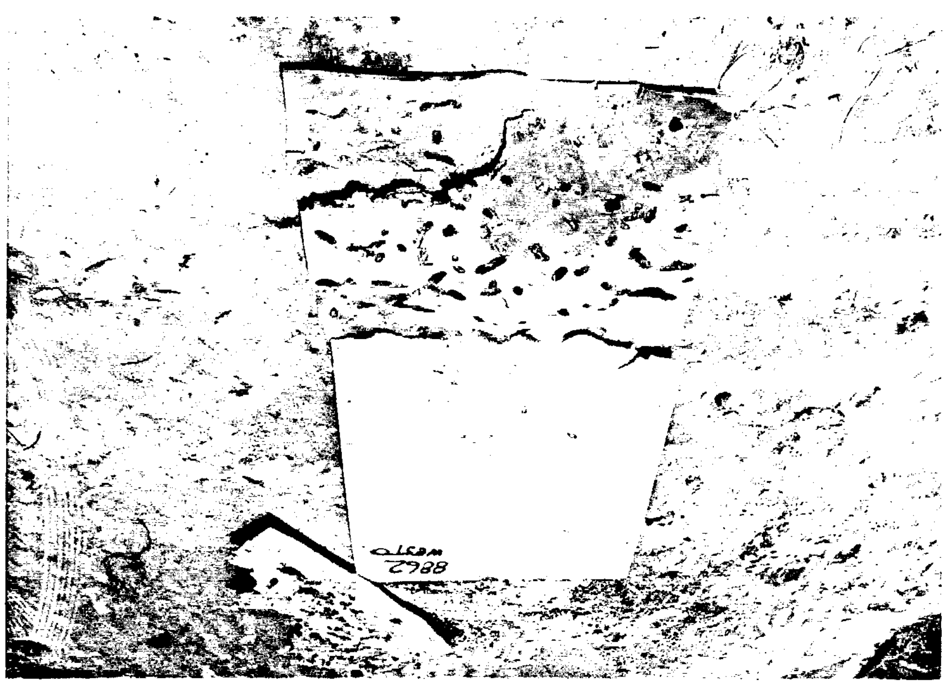

Figure 27: Side Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 3

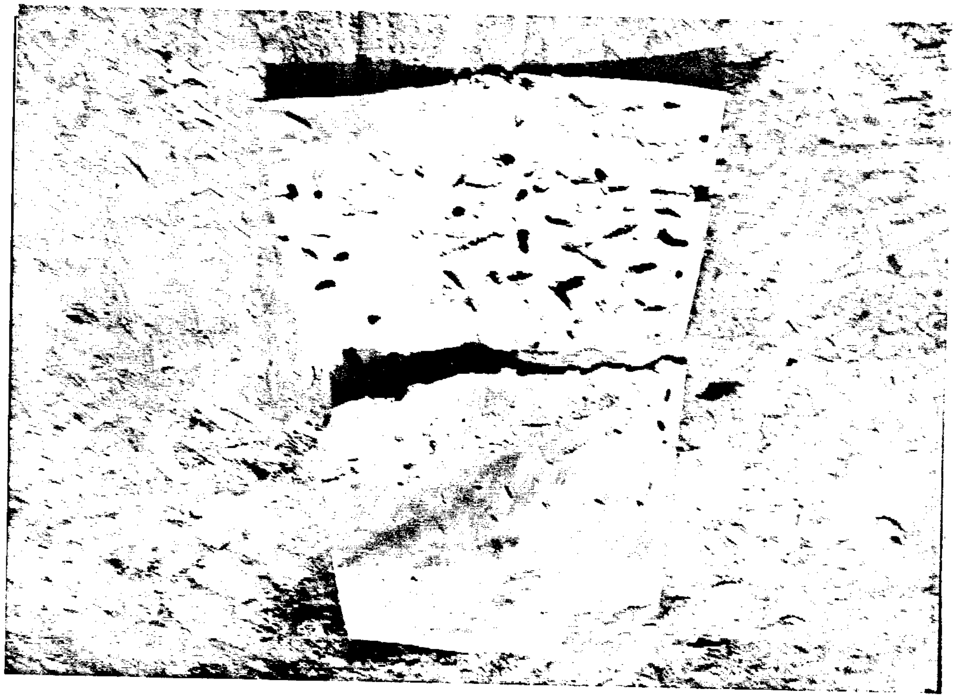

Figure 28: Side Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 3

Figure 29: Top Witness Plate from Baseline AFX-644 Sympathetic Detonation Test 3

Section Three: First AFX-644 Reformulation Program

The responses observed in hazards testing of the baseline AFX-644 formulation were promising. The results of sympathetic detonation testing were mixed. The scaled up mixes of baseline AFX-644 had lower than expected charge densities with an attendant rise in shock sensitivity. The ingredient suspected of causing the inconsistencies in processing was the D2 wax. Other parts of the formulation were also scrutinized. Several shortcomings of the D2 wax composition were revealed during characterization and evaluation of the baseline formulation. These shortcomings were significant enough to prevent AFX-644 from becoming a qualifiable bomb fill. A reformulation strategy was developed to: minimize exudation, improve processing parameters, and improve AFX-644 survivability for sympathetic detonation scenarios.

Several varieties of waxes in numerous concentrations and wax to surfactant ratios were evaluated. An improved formulation with the same composition percentages as the baseline formulation (TNT/NTO/wax/Al 30/40/10/20) was developed and designated AFX-644 Mod 0. AFX-644 Mod 0 employs a high melting microcrystalline wax, called Indramic-800 and an alternative surfactant called Ganex WP-660 in the percentages reported in Table III. The objectives of the reformulation strategy and the results of formulation changes are discussed in the following sections.

Table III: AFX-644 Wax Compositions

Baseline D2 Wax Melt Point = 62.7°C	**Improved Wax** Melt Point = 83.9°C
Indramic-170C 84%	Indramic-800 98.5%
Nitrocellulose 14%	Ganex WP-660 1.5%
Lecithin 2%	

3.1 Minimize Exudation

Although D2 wax containing Indramic-170C is routinely used in Composition B (RDX/TNT/D2), the percentage employed is very small (0.5%). Also, the influence of wax migration and exudation are not an issue for Comp B. AFX-644 cannot tolerate migration and exudation of the wax, since this may dramatically influence its responses to hazardous stimuli. Studies on the baseline AFX-644 formulation determined that at least 8% (predominantly wax) of the formulation was exuding during pressurized temperature cycling between -64°C and +74°C --an unacceptable finding.

The strategy selected to minimize exudation was to replace the D2 with a wax possessing a higher melting point. Reduced wax and waxless formulations were also studied. The exudation measured for AFX-644 Mod 0 samples subjected to pressurized temperature cycling was 0.43%. Acceptable growth characteristics were also observed with expansions of 2.56% in length and 2.34% in diameter for the 1-inch by 1-inch cylindrical samples--typical for TNT systems.

3.2 Improved Processing Parameters

For an explosive formulation to be viable for qualification, consistent liquid viscosities and charge densities must be achievable. Batch viscosities of the baseline AFX-644 mixtures ranged from a very castable fluid to thick/pasty compositions. Resulting charge densities ranged from below 90% of the theoretical maximum density (TMD) to greater than 96% TMD. Several factors which contributed to these large variations in processing parameters were identified and eliminated.

3.2.1 Minimization of Nitrocellulose

It was determined that nitrocellulose decomposition from the D2 wax is a source of off-gassing which could result in micro-void formation as the molten explosive cools and freezes. Steps were taken to reduce the percentage of nitrocellulose employed in the wax formulation. The D2 formulation contains 14% nitrocellulose. It was determined that stable TNT/wax emulsions could be formed using as little as 2% nitrocellulose in the wax formulation with I-170C. Other mineral and petroleum waxes required only 0.5% nitrocellulose to form TNT emulsions.

It was also learned that the influence of nitrocellulose decomposition on charge quality could be minimized by preprocessing the wax/nitrocellulose formulation to remove any gases formed by nitrocellulose decomposition. This is accomplished by melting the wax mixture and applying a vacuum to the melt kettle for approximately 15 minutes.

3.2.2 Alternative Surfactant Systems

Alternative surfactant systems were also studied to replace completely the nitrocellulose/lecithin system employed in D2 wax. MACH I of King of Prussia, PA, under contract to the USAF, conducted a systematic investigation of nearly 300 processing aids using nitromethane as a TNT simulant. Ganex WP-660 was recommended for trials with TNT and the I-170C wax. Ganex is a poly-(vinyl-pyrolidone/1-triacontene) dispersing agent commonly used in the cosmetics industry to form stable emulsions[4]. The USAF performed TNT/I-170C/Ganex trials and found the emulsion characteristics of this system to be significantly improved when compared with the nitrocellulose/lecithin system. Subsequent shock sensitivity testing and critical diameter experiments of AFX-644 Mod 0 with this wax indicated increased critical diameter and dramatic reductions in shock sensitivity when compared to the baseline formulation. It was also determined that the emulsion reduced energy release as measured by cylinder expansion tests.

3.2.3 NTO Specification

It was determined that lot to lot variations in the nitrotriazolone (NTO) purchased from Olin and Dynamit Nobel influenced end-of-mix (EOM) viscosities. Sieve and scanning electron microscopy analyses were performed to determine the particle size distribution and crystal morphology for each lot of NTO. The results of these analyses led to the development of a single parameter, packing density, which accommodates all of the observed variations. Packing density is determined by mildly vibrating a known mass of particles to a final volume. It was determined that an NTO packing density of greater than or equal to 0.95 g/cc is required to achieve castable viscosities for AFX-644. The specification for NTO was altered as follows:

Particle Size: No more than 20% of the material will pass through a 212 micron (70 mesh) sieve;

Packing Density: Greater than or equal to 0.97 grams/cm^3; and

Method: A know mass of material is vibrated mildly (so as not to crush or mechanically damage the crystals) until a minimum volume is achieved. The packing density is then calculated with this final volume.

A STANAG specification is in preparation with consideration of this data. This specification was achieved in a recent procurement of NTO from Dynamit Nobel via Girundus Corporation, and end-of-mix viscosities are consistently castable with this material. The 14 lots received from Dynamit Nobel in FY93 had the particle size distributions shown below:

Table IV: Particle Size Distributions of NTO Lots from Dynamit Nobel

Particle Size (microns)	Percent, %	Range, %
>600	11.3 ± 10.2	0.2-29.5
600-425	32.8 ± 9.3	16.4-46.1
425-300	28.3 ± 6.9	20.5-44.6
300-212	15.2 ± 6.7	9.2-28.7
<212	12.3 ± 3.9	7.1-18.4
The packing densities of the lots received were: 1.04 ± 0.02 g/cc.		

3.2.4 Vacuum Processing

Entrapped air which enters the molten explosive during mixing was determined to be another source of charge density variations. A processing step of applying vacuum (28 inches Hg) on the melt kettle for approximately 15 minutes during mixing was added. The kettle atmosphere is slowly (so as not to drive air back into the mixture) returned to ambient pressure prior to casting. Charge densities for Mk-82 bombs loaded with AFX-644 Mod 0 using this technique have been very consistent. The average density for the first nine bombs loaded with this formulation varied by only 0.4%.

3.3 Improve Survivability for Sympathetic Detonation Scenarios

3.3.1 AFX-644 Shock Sensitivity

Figure 30: Modified Expanded Large Scale Gap Test Set-Up

A variety of TNT/NTO formulations were studied for comparison with the baseline AFX-644 formulation. The shock sensitivities of several TNT/NTO compositions were measured using the Modified Expanded Large Scale Gap Test[5] (ELSGT)(Figure 30). Reduced wax and waxless formulations were studied to minimize exudation as mentioned above. Alternative waxes and surfactant systems were also employed. The I-800/Ganex WP-660 wax/surfactant system was most effective in reducing the shock sensitivity of the AFX-644 formulation. The results of this testing is presented in Table V. The last three rows of Table V concern explosives developed in the second reformulation effort which is discussed in Section Four.

Table V: Expanded Large Scale Gap Test Results for Various AFX-644 Formulations

AFX-644 Variants	**Formulation**				**Density**		**ELSGT**	
	TNT	NTO	Wax and Type	Al	g/cc	TMD	Go (Inches)	No Go (Inches)
Baseline	30%	40%	10% D2 [3]	20%	1.68	94.4%	1.91	1.94
Other Iterations	30%	40%	10% I-800 [5]	20%	1.69	96.0%	2.44	2.47
	28%	40%	12% I-800 [5]	20%	1.68	96.5%	2.32	2.35
	28%	40%	4% PW-500 [6]	28%	1.84	96.3%	2.15	2.19
	26%	40%	4% PW-500 [6]	30%	1.84	95.3%	2.07	2.09
	26%	40%	6% PW-500 [6]	28%	1.82	96.7%	1.94	2.00
	26%	40%	6% PW-600 [6]	28%	1.73	92.0%	2.06	2.13
Waxless	30%	40%	None	30%	1.92	96.0%	2.24	2.25
Mod 0 [1]	30%	40%	10% I-800 [4]	20%	1.71	97.2%	1.50	1.63
Mod 0 [2]	30%	40%	10% I-800 [4]	20%	1.75	99.4%	1.25	1.31
Mod 1 [1]	30%	45%	10% I-800 [4]	15%	1.68	97.4%	1.76	1.81
Mod 2 [1]	32%	45%	8% I-800 [4]	15%	1.64	93.4%	1.94	2.00
AFX-645 [1]	32%	48%	8% I-800 [4]	12%	1.63	93.6%	1.95	2.01

Notes: 1: Vacuum Mix, Ambient Cast ($V_D = 6.82 \pm 0.12$ km/sec, 2.0 in $\leq D_c \leq$ 2.5 in.)
2: Vacuum Mix, Vacuum Cast
3: D2 wax is 84% Indramic 170C, 14% Nitrocellulose and 2% Lecithin (melting point 62.7°C)
4: 98.5% Indramic 800 wax and 1.5% Ganex surfactant (melting point 83.9°C)
5: 94% Indramic 800 wax, 4% Nitrocellulose and 2% Lecithin
6: PW = Polywax

3.3.2 New Metal Pallet

Suppression of sympathetic detonation was achieved through optimization of candidate explosive formulations and container design. Most munitions are stored in containers where the packaging material and container, by design or coincidence, provide considerable protection in a sympathetic detonation scenario. This is not true for general purpose bombs which are stacked in groups of six in simple, open pallets (Figure 16). However, during the course of the FIGPB program, a new standard metal pallet was introduced. The new design was accomplished to enable munition handlers using forklifts to dissect bomb pallets for maneuvering as "three-packs" or "six-packs." The separation distance between rows and columns in the old standard metal pallet is approximately 0.5 inches. The new pallet provides a horizontal distance between bombs of approximately 0.75 inches and the top row of bombs has been raised to a spacing of approximately 2.88 inches (Figure 31). In this case, the survivability of the bombs is aided by the change.

As reported by Glenn, et. al. [6], pallet dimensions dramatically influence the response of the items to detonation events. The response of the acceptor items to the donor stimulus is a complicated function of casewall thickness, velocity and shape at the point of donor casewall impact with the acceptor bomb. It has been determined experimentally and by HULL hydrocode calculations[6,7] that the diagonal positions are the worst acceptor positions for surviving sympathetic detonation in the old pallet when the bottom, center item is employed as the donor. The acceptor bombs directly above and adjacent to the donor bomb provide a symmetrical passage along the diagonal for the expanding donor casewall. The donor casewall impacts both top and adjacent acceptor simultaneously causing both case fracture at the impact points and a corresponding increase in pressure at these points. This results in a fragment which does not thin appreciably as it accelerated further towards the diagonal acceptor. More importantly, the edges of this casewall passing between the top and adjacent bomb accelerate more than the center thus creating a nearly flat plate to impact the diagonal acceptor.

The shock wave from the flying casewall of the donor can be reduced by lateral release waves as it travels through the case of the acceptor. These lateral release waves will affect the pressure at the explosive/case interface to varying degrees depending on the donor case thickness and shape at impact. The diagonal bomb in the old metal pallet was being struck by a fairly flat casewall which increases the impact area and reduces the effect of these lateral pressure release waves. This combination of pulse duration and high peak pressure allow the diagonal bomb to detonate when those closer to the donor do not.

When the bomb separation distances are increased slightly, as with the adjacent and top bombs in the new metal pallet, the peak pressure in the acceptors will increase due to the added room the casewall has to accelerate. As even more separation is provided, as with the diagonal bombs of the new metal pallet, the casewall thins further and the peak pressure then decreases due to lateral release waves. The response of the acceptors depends on both peak pressure and pulse duration. This dependence on pulse duration is due to two physical effects: the lateral release waves mentioned above and a phenomenon of detonation referred to as critical energy. The pulse duration in the explosive will effect the amount reacted if sufficient energy is not available to create a prompt detonation. For example, a 65 kbar pulse of very short duration may result in only a thin region of explosive reacting while a longer duration pulse of the same peak pressure would allow the acceptor to run up into a full self-sustaining detonation.

To illustrate this complex interrelation of pressure, velocity and impulse, calculations and test results for AFX-1100 explosive are given. Table VI shows the velocities, pressures and impulse inside the acceptor generated by an AFX-1100 donor at the point of first casewall impact with the acceptor for the old standard pallet and pallets in which the top row of bombs was raised. This table is generated from HULL calculations. The results of MK-82 sympathetic detonation testing of AFX-1100 are provided in Table VII for the old standard pallet and pallets in which the top row of bombs was raised. As the top row is raised, the casewall accelerates to a higher velocity and the peak pressure increases in the top center bomb and decreases in the diagonal bomb. The impulse imparted to the diagonal bomb diminishes, while the that at the top center bomb passes through a maximum due to an "optimal" case thickness/velocity combination.

HULL calculations were also performed for donor bombs containing a 30/40/2/28 -- TNT/NTO wax/Al AFX-644 formulation[8]. Although this particular formulation was not explored further, the trends of pressure distribution within the pallets during a sympathetic detonation test are valid. The pressure and velocity distributions in the old standard pallet and the new standard pallet are shown in Table VIII. The maximum impulse in the old standard pallet is observed by the adjacent and top bombs. With this donor system, the diagonal bomb is subjected to a very large peak pressure relative to the other items. The peak pressure distribution is much more uniform in the new standard pallet configuration. In the new standard pallet, the critical position for surviving sympathetic detonation has shifted to the adjacent bombs. The donor casewall impacts these items first. The expansion at impact with these acceptors is smaller than the expansion at the point the donor casewall impacts the top center bomb or the diagonal bombs. Also, the casewall is somewhat thicker at the point of impact with the adjacent bomb, creating a longer duration pulse in this location.

Table VI: Pressure/Velocity Calculations for MK-82s Containing AFX-1100 with 0.5-inch Horizontal Separations at Various Vertical Separation Distances[7]

	Adjacent Bomb			
Top Row Position	Distance From Donor mm	Casewall Velocity mm/µsec	Peak Pressure kbar	Impulse kbar*secX10^5
All Palllets	13	1.04	28	1.27
	Top Bomb			
Old Standard	13	1.04	28	1.27
Raised to 2 Inches	51	1.33	36	1.40
Raised to 3 Inches	76	1.37	38	1.48
Raised to 5 Inches	128	1.44	45	1.45
	Diagonal Bomb			
Old Standard	133	1.5	55	1.30
Raised to 2 Inches	159	1.58	47	1.29
Raised to 3 Inches	177	1.63	44	1.12
Raised to 5 Inches	219	1.73	39	0.84

Table VII: AFX-1100 MK-82 Sympathetic Detonation Test Results with 0.5-inch Horizontal Separations at Various Vertical Separation Distances[6]

Top Center Separation Distance (mm)	Diagonal Separation Distance (mm)	Diagonal Acceptor Response
Old Standard Pallet	133	Detonation
41	160	Detonation
76	180	No Detonation
83	200	No Detonation
133	230	No Detonation

Table VIII: 2% Wax AFX-644 Pressure/Velocity/Impulse Distributions for Acceptors in Old And New Standard Metal Pallet Configurations[8]

Pallet and Acceptor Position	Distance (mm)	Casewall Velocity (mm/µsec)	Peak Pressure (kbar)	Impulse (kbar*sec*10^5)
Old Pallet Adjacent Bomb	13	1.29	58	2.76
Old Pallet Top Bomb	13	1.29	58	2.76
Old Pallet Diagonal Bomb	133	1.69	92	2.11
New Pallet Adjacent Bomb	19	1.47	73	2.74
New Pallet Top Bomb	73	1.60	72	2.24
New Pallet Diagonal Bomb	179	1.73	75	1.72

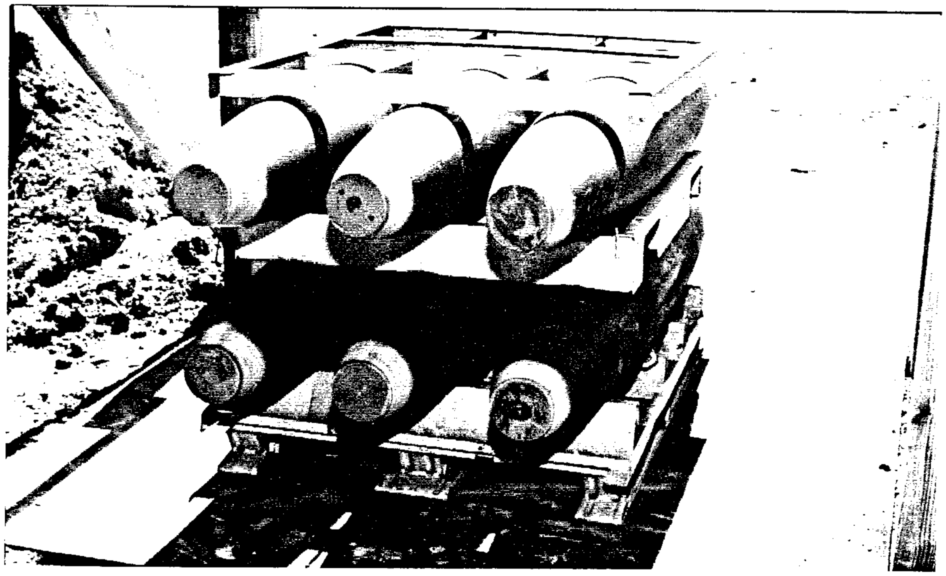

Figure 31: New Standard Mk-82 Metal Pallet

Several storage pallet configurations were tested to determine their influence on the survivability of AFX-644 filled bombs and to establish safety margins for the standard pallet configuration. As discussed previously, the baseline AFX-644 formulation survived consistently in the adjacent position when the bottom center item in the pallet was detonated as the donor bomb. Mixed results were observed for acceptor bombs in the diagonal position. An asymmetric pallet test was designed for testing to allow more information to be gathered from a single test and to provide design safety margins. The asymmetric pallet test is described in the next sub-section.

3.3.3 Sympathetic Detonation Testing of First Reformulation Candidates

A series of sympathetic detonation experiments employing an asymmetrical pallet configuration was conducted for three different TNT/NTO formulations. The separation distance between the center column of bombs and one of the adjacent columns was 2.0 inches, while the separation distance between the center column and the other adjacent column was 4.0 inches. The separation distance between the top and bottom rows of the pallet was 0.5 inches. The donor bomb was the bottom item in the center column. Live acceptor bombs were placed in the top position of each adjacent column (Figure 32). Witness plates surrounded the test pallet and served as a means of data collection along with the pre-stamped cases. This configuration enabled the simultaneous evaluation of the worst case donor/acceptor orientations for two distinctly different pallet designs. A substantial margin of safety is established for the vulnerability of formulations which survive the Mk-82 sympathetic detonation test at a separation of 2 inches. The results of this testing is summarized in Table IX.

Table IX: Results of Asymmetric Pallet Testing

AFX-644 Formulation	Result @ 2-inch Spacing	Result @ 4-inch Spacing
TNT/NTO/Al 30/40/30 (waxless)	Go (Figure 33 Left)	Go (Figure 33 Right)
TNT/NTO/PW-500/Al 26/40/4/30 (low wax)	Go (Figure 34 Left)	No Go (Figure 34 Right)
TNT/NTO/I-800/Ganex/Al 30/40/9.85/0.15/20 (AFX-644 Mod 0)	No Go (Figure 35 Left)	No Go (Figure 35 Right)

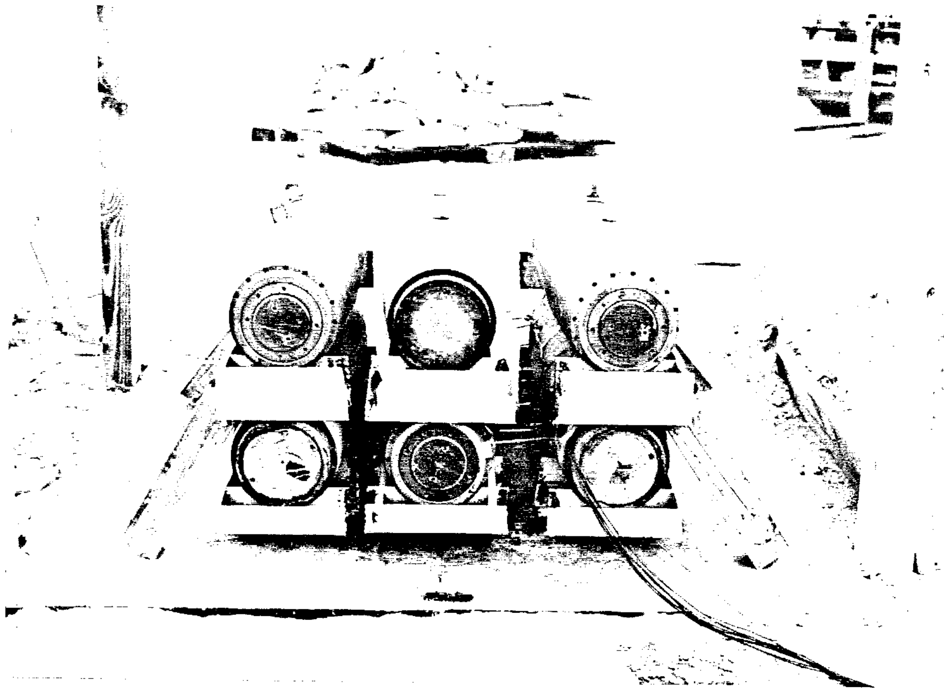

Figure 32: Asymmetrical Pallet Used to Evaluate Candidate Explosives in Sympathetic Detonation

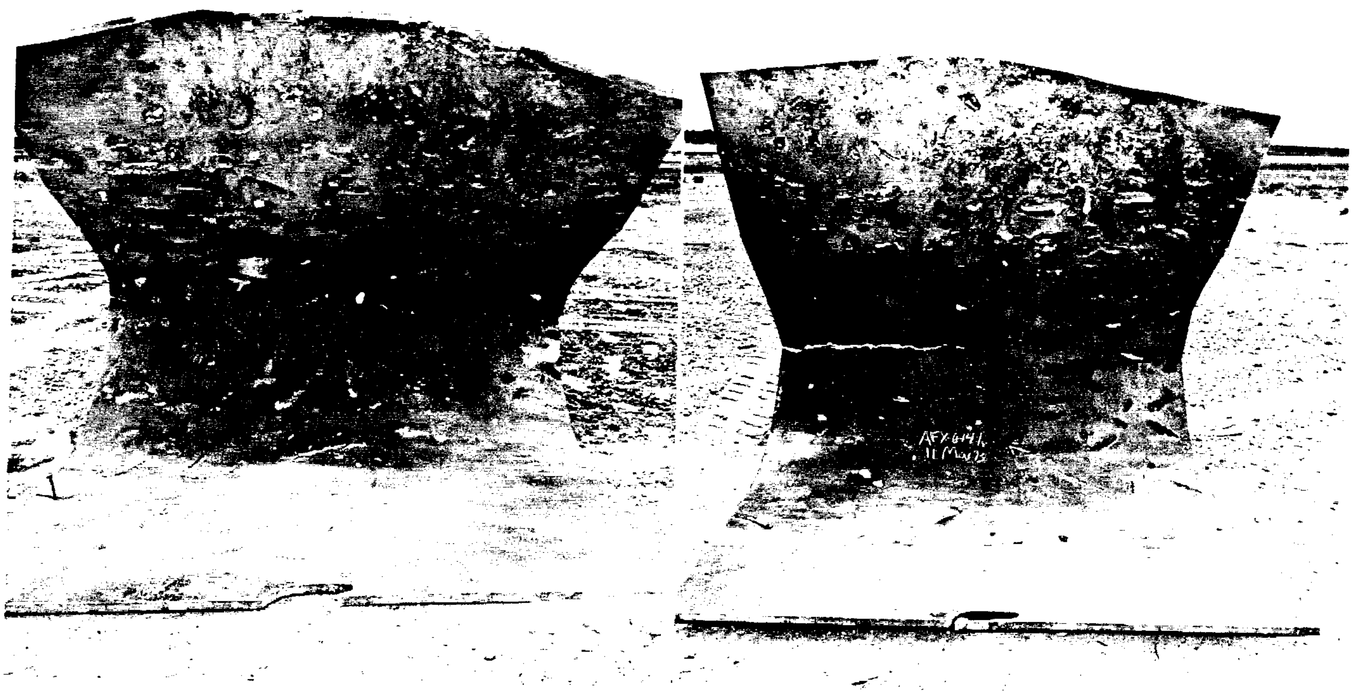

Figure 33: Side Witness Plates from AFX-644 Waxless Asymmetrical Pallet Sympathetic Detonation Test

Figure 34: Side Witness Plates from AFX-644 Low Wax Asymmetrical Pallet Sympathetic Detonation Test

Figure 35: Side Witness Plates from AFX-644 Mod 0 Asymmetrical Pallet Sympathetic Detonation Test

3.3.4 AFX-644 Mod 0 All Live Sympathetic Detonation Test

An all live sympathetic detonation test of AFX-644 Mod 0 was also conducted in the new standard metal pallet. All items were loaded using a 30 gallon kettle. Prior to casting at ambient pressure, the ingredients were mixed under vacuum conditions (28 in. Hg) for approximately 15 minutes. This processing procedure was employed for all subsequent loadings of AFX-644 modifications. The only exception were the vacuum cast split molds used in the 4-inch diameter copper cylinder expansion tests discussed in section 4.1. The donor bomb was placed in the bottom, center position of the six-member pallet and was initiated from the nose fuzewell using composition C-4. The use of non-electric initiation and deletion of the piezoelectric pins was done to reduce the cost of the experiment. As in previous Mk-82 sympathetic detonation tests, 1-inch thick armor plates surrounded the pallet of bombs as witness panels.

The vertical separation between the rows of bombs was approximately 2.83 inches, while the separation between columns was approximately 0.99 inches. The detonation of the donor bomb did not propagate to any of the acceptor bombs as evidenced by witness plates, case remnants and residual explosive recovered after the test. The bottom witness panel exhibited the typical scarring generated by donor bombs (Figure 36). No scarring of the edges, typical of adjacent bomb detonations was observed. The top witness panel was recovered as a single piece with minor scarring from donor fragments and mild denting/deformation from the impact of the top-center acceptor bomb (Figure 37). The recovered witness panels from the sides of the pallet were essentially identical to each other (Figure 38). They were both smooth with the exception of mild impacts from donor fragments. Unreacted explosive residue was found in and about the test arena, Large, thick, positively identified pieces of all of the acceptor bombs were recovered (Figures 39-43). One of the diagonal acceptor bombs was almost entirely recovered. Many of the recovered pieces were glazed with explosive residue. One of the adjacent bomb remnants contained significant amounts of unreacted high explosive. Although extremely successful from an insensitivity standpoint, the relatively low damage to the acceptor bombs was (in hind sight) indicative that performance of the donor was less than had been observed with baseline AFX-644.

Figure 36: Bottom Witness Plate for All Live AFX-644 Mod 0 Sympathetic Detonation Test

Figure 37: Top Witness Plate for All Live AFX-644 Mod 0 Sympathetic Detonation Test

Figure 38: Side Witness Plates for All Live AFX-644 Mod 0 Sympathetic Detonation Test

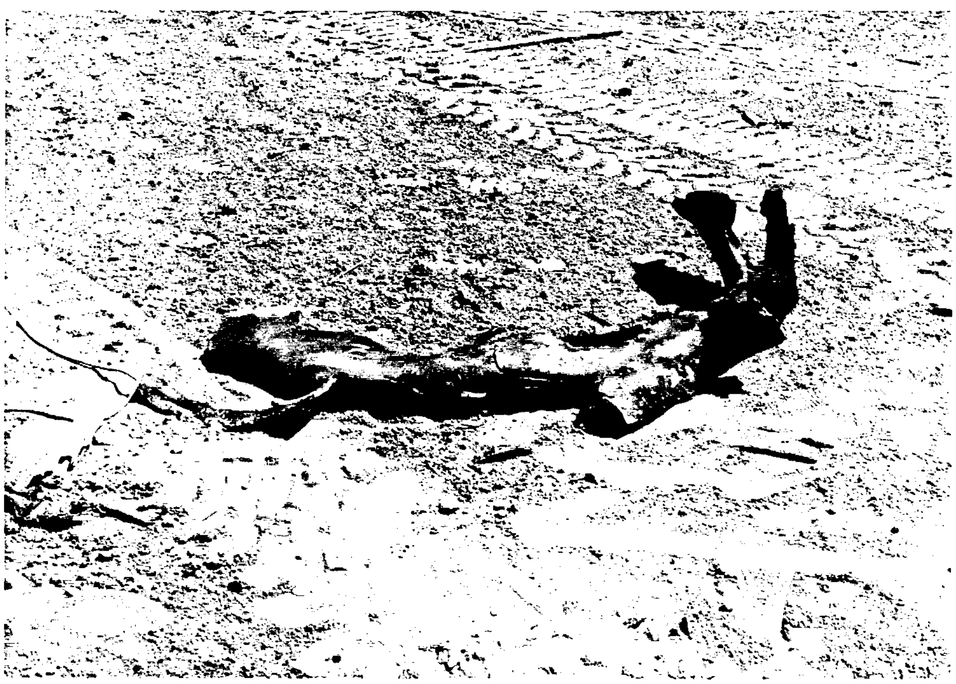

Figure 39: Adjacent Acceptor for All Live AFX-644 Mod 0 Sympathetic Detonation Test

Figure 40: Adjacent Acceptor for All Live AFX-644 Mod 0 Sympathetic Detonation Test

Figure 41: Top Center Acceptor for All Live AFX-644 Mod 0 Sympathetic Detonation Test

Figure 42: Diagonal Acceptor for All Live AFX-644 Mod 0 Sympathetic Detonation Test

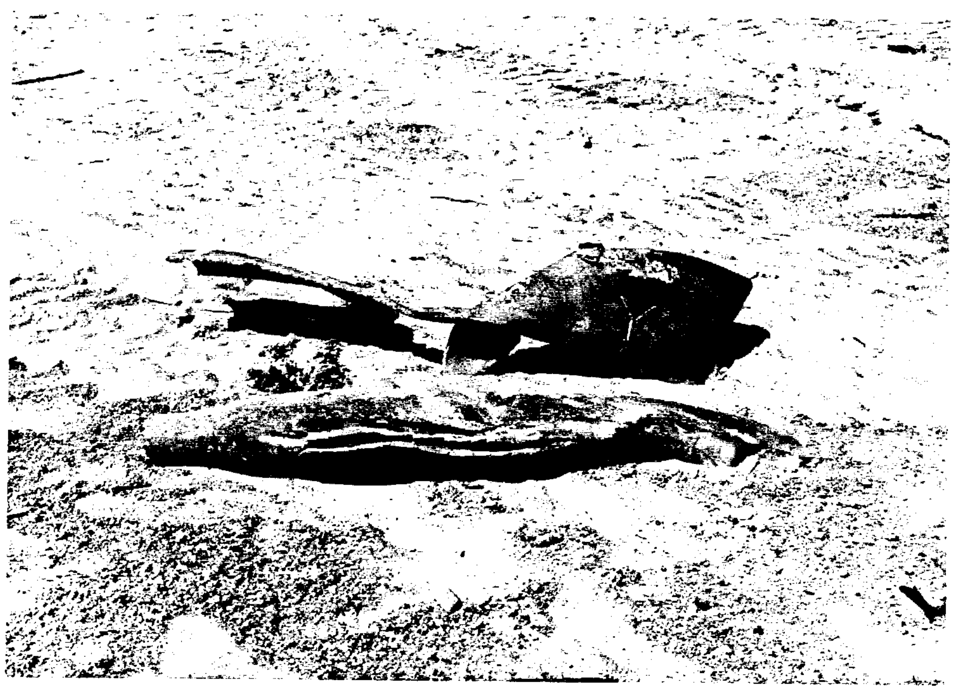

Figure 43: Diagonal Acceptor for All Live AFX-644 Mod 0 Sympathetic Detonation Test

Section Four: Second AFX-644 Reformulation Program

After the all live AFX-644 Mod 0 sympathetic detonation test a Mk-82 blast arena test was conducted to augment the data from a baseline AFX-644 blast performance test. This AFX-644 Mod 0 test showed that the performance of the explosive had suffered from the reformulation despite having the same percentage of energetic material. However, AFX-644 Mod 0 is far less sensitive than was required to pass the sympathetic detonation test as shown in Table IX. A second reformulation strategy was devised to trade some of this additional insensitivity for energetic material to enhance performance. This section explains the performance measurements for all AFX-644 variants tested, the results of the second reformulation and the sympathetic detonation testing of these newer formulations. AFX-645 was the product of this second reformulation effort.

4.1 Four-Inch Diameter Copper Cylinder Expansion Tests

Copper cylinder expansion tests (4-inch diameter) were conducted for the baseline AFX-644, AFX-644 Mod 0, AFX-644 Mod 1 and AFX-645 in addition to tritonal. Procedures described in Reference 9 were employed in these tests. The test set-up is shown in figure 44. A low-oxygen, high conductivity copper tube with an inner diameter of 101.6 mm, a wall thickness of 10.16 mm and a length of 604 mm contained 6 cylindrical pellets of the candidate explosive. Each pellet had a length of 101.6 mm and was machined to fit within the cylinder. The pellets were stacked within the cylinder. The initiation train consisted of an 1E23 electronic bridge wire (EBW), a P-040 plane wave lens ($TNT/CaCO_3$), and a 101.6 mm diameter, 50.8 mm long cylinder of comp B.

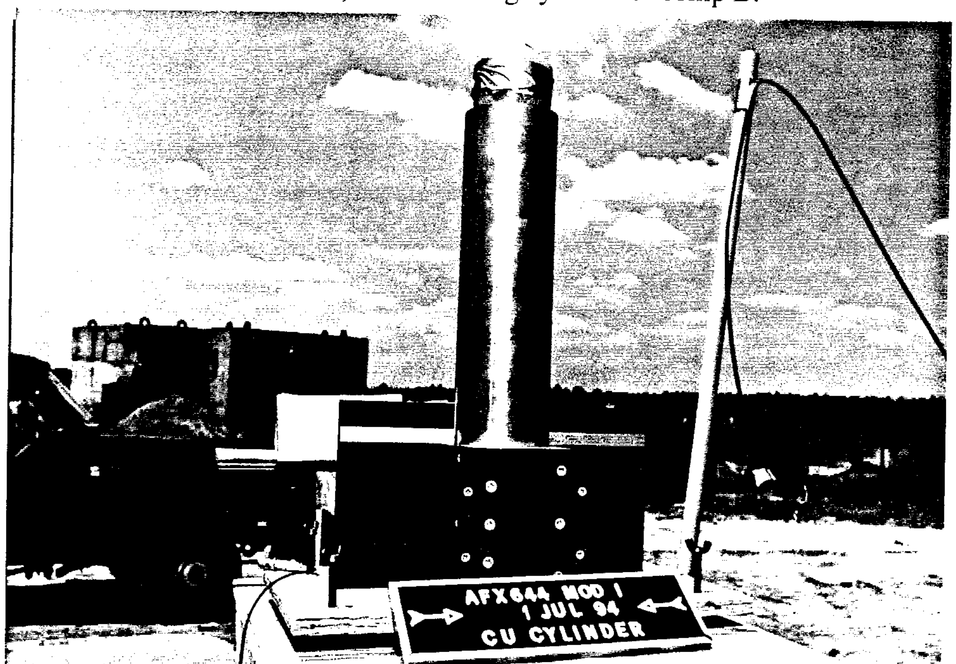

Figure 44: Four Inch Copper Cylinder Expansion Test Set Up

The radial motion of the copper wall was measured shadow-graphically using a Cordin model 132A high speed streak camera with a 400 mm focal point lens. A writing speed of approximately 2.0 km/sec was used for the baseline AFX-644 shot. A writing speed of approximately 1.5 km/sec was employed for the other formulations. The camera slit was positioned 177.8 mm from the bottom of the cylinder. Back-lighting was provided by two argon candles positioned behind the cylinder. The argon in the candles was illuminated by shocks created by 100 mm square, 25.4 mm thick octol (75/25) pads. The pads were initiated simultaneously with separate 25.4mm diameter, 25.4 mm long comp A5 pellets and RP-2 EBW detonators. The illuminating end of the argon candles was fitted with a 6 mm thick, white Delrin plastic diffuser and placed approximately 400 mm from the rear surface of the copper tube. The cylinder was placed approximately 975 cm from the camera, providing a field of view of approximately 366 mm in width to obtain readings beyond 120 mm on each side of the cylinder.

As shown in figure 44, an aluminum alignment fixture is used to position the cylinder. A graduated steel ruler is attached to the alignment fixture for determination of the optical magnification from a static photograph. Both edges of the film record were analyzed on an Optical Gauging Products Model XL-14C comparitor to obtain the casewall position as function of time. The optical comparitor results were transposed to the displacement domain and then curve fitted to a nonlinear form employed by Davis[10]:

$$V_x = \frac{A\left(\frac{3}{2}\sqrt{\frac{x}{B}} + \frac{x}{B}\right)}{\left(1+\sqrt{\frac{x}{B}}\right)^2}$$

where V_x is the wall velocity (mm/usec) at any given displacement x (mm) and A and B are fitting constants. Gurney constants were derived from the curve fit velocities at a casewall displacements of 24 mm, 76 mm and 120 mm using:

$$G_{76} = V_{76}\sqrt{M/C + .5}$$

where G_{76} is the Gurney constant (km/sec) calculated using the velocity at 76 mm (equivalent to 19 mm for the 1 inch diameter test), V_{76} is the wall velocity at 76 mm of expansion and M/C is the mass ratio of metal to explosive. Gurney energies were calculated using:

$$E_{g76} = ME_{76}\left[\frac{1+\rho_0\frac{W}{2M}}{W}\right]$$

where E_g is the Gurney energy (kJ/cm^3), E_{76} is the specific kinetic energy of the casewall (1/2 V_x^2) at 76 mm of expansion, M is the mass of the cylinder wall per unit length, W is the volume of the cylinder wall per unit length, and ρ_0 is the initial density of the explosive. Data for each of the formulations tested is provided in Table X. A comparison of the performance for each formulation with the performance of tritonal is also provided.

Table X: 4-inch Diameter Copper Cylinder Expansion Data for Tritonal and AFX-644

Formulation	Casewall Velocity (Km/sec)			Gurney Energy (KJ/cm)	Gurney Velocity (Km/sec)	Ratios with Tritonal	
	V_{24}	V_{76}	V_{120}	E_{g76}	G_{76}	$E_{g76}/E_{g76}(T)$	$G_{76}/G_{76}(T)$
Tritonal	1.12±0.02	1.34±0.00	1.41±0.01	4.23±.01	2.23±0.00	1	1
Baseline AFX-644	1.10±0.01	1.29±0.03	1.35±0.04	3.94±.19	2.16±0.06	0.93±0.05	0.97±0.03
AFX-644 0	1.01±0.03	1.14±0.04	1.18±0.04	3.09±.19	1.90±0.06	0.73±0.05	0.84±0.03
AFX-644 1	1.04±0.02	1.19±0.01	1.24±0.00	3.35±.05	1.99±0.01	0.79±0.01	0.89±0.01
AFX-644 3	1.10±0.01	1.28±0.03	1.33±0.03	3.85±.16	2.14±0.05	0.91±0.04	0.95±0.02

4.2 Balancing Performance with Sensitivity

Development of an insensitive high explosive requires achieving the appropriate balance of sensitivity and performance while maintaining a reasonable level of initiability. All AFX-644 Mods are readily initiated as explained in the next section of this report. Maximum performance is desired while still achieving the criteria for passing the sympathetic detonation test. Energy/Sensitivity ratios for various formulations were determined using the Gurney Energy at a case wall expansion of 76mm, Eg_{76} and the calibrated pressure corresponding to the minimum barrier thickness in the modified expanded large scale gap test required to prevent detonation of the acceptor charge, P_{NOGO}. Given two formulations within the same family of formulations which yield different sympathetic detonation results, (i.e. one propagates and one does not propagate) one can add energetic material to the non-propagating formulation until the energy/sensitivity ratio approaches that of the propagating formulation. This is the approach used to develop AFX-645 as shown in Table XI. The energy/sensitivity ratio for AFX-644 Mod 0 which survived sympathetic detonation testing in the asymmetrical pallet is 0.0358. The energy/sensitivity ratio of the waxless formulation (TNT/NTO/Al-30/40/30) which failed to survive sympathetic detonation testing in the asymmetrical metal pallet is 0.0624. A target value for reformulation of AFX-644 Mod 0 was provided by the baseline AFX-644 formulation (0.0533) which yielded mixed sympathetic detonation results in the old standard metal pallet. AFX-645 was selected based on its energy/sensitivity ratio of 0.0543.

Table XI: Energy to Sensitivity Ratios for Various AFX-644 Formulations

AFX-644 Variants	Formulation				Density		Symp. Detonates	Eg_{76}/ P_{NOGO}
	TNT	NTO	Wax and Type	Al	g/cc	TMD		
Tritonal	80%	none	none	20%	1.73	96.6%	Go	0.2213
Baseline	30%	40%	10% D2	20%	1.68	94.4%	Mixed	0.0533
Waxless	30%	40%	None	30%	1.92	96.0%	Go	0.0624
Mod 0 **	30%	40%	10% I-800	20%	1.71	96.2%	No Go	0.0358
Mod 1 *	30%	45%	10% I-800	15%	1.68	97.4%	not tested	0.0423
AFX-645*	32%	48%	8% I-800	12%	1.63	93.6%	No Go	0.0543

4.3 Blast Pressure Testing

Mk-82 pressure arena tests were conducted for the baseline AFX-644 formulation, AFX-644 Mod 0, AFX-645, H-6 and tritonal. Data for each of these tests are summarized below. The transducers were placed in two radial arrays at ten feet intervals in a range of 25 to 65 feet. For each shot, the test item was positioned horizontally on a wooden stand, with its centerline 54.0 inches above ground level. The stand was positioned above two 5 ft x 10 ft x 4-inch thick, rolled homogeneous armor plates butted together along the 10 ft edge. The bomb stand straddled the joint between the plates. The pressure transducers were positioned as shown in the layout diagram (Figure 45). For the AFX-645 test, fragment velocity screens were placed at a distance of 45.8 ft from the test item for comparison with previous data from tritonal. A total of 12 each, 4 ft wide X 8 ft tall screens were positioned to register time-of-arrivals (TOAs) for fragments from 5° polar zone increments ranging from 65-125° (i.e., panel 1 registered fragments from 65-70°, panel 2 registered fragments from 70-75°, etc.). The results presented in this section were gathered over a span of four years. The test set up, instrumentation, data collection and data analysis were repeated as identically as possible for these tests. Tritonal shots were conducted towards the end of the program as earlier data were not collected identically. The earlier tritonal data are not reported here.

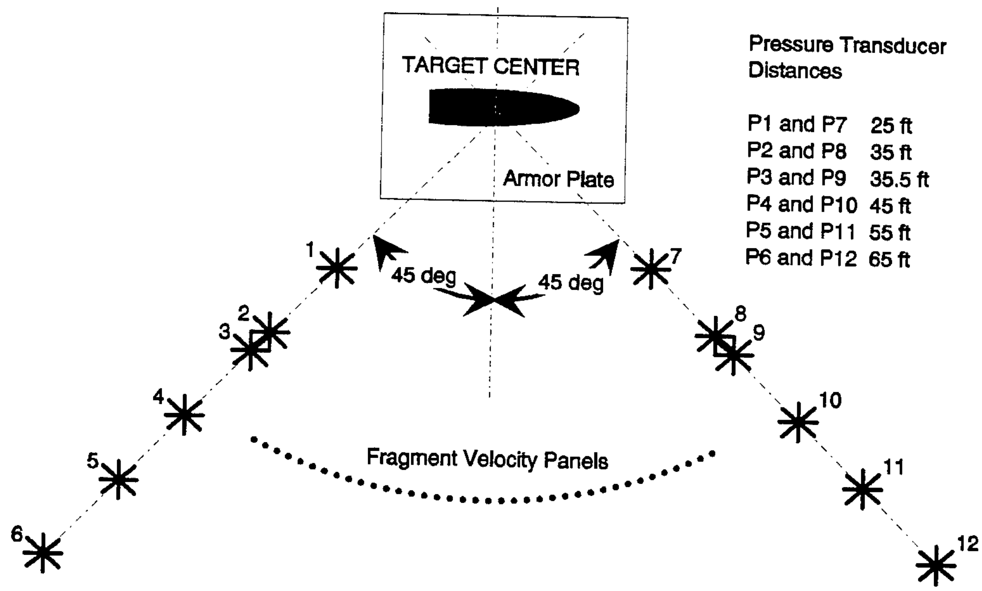

Figure 45: Arena Layout for Mk-82 Blast Pressure Testing

Figure 46 displays the time of arrival of the blast wave plotted against pressure gauge location. This graph gives a good idea of relative performance as the strongest pressure wave should travel faster in air of the same temperature. These data were taken on several different days and not corrected to a standard day. In order from most powerful to least, this graph would rank the explosives as: H-6, then baseline AFX-644 and Tritonal tied for second, then AFX-645 then AFX-644 Mod 0.

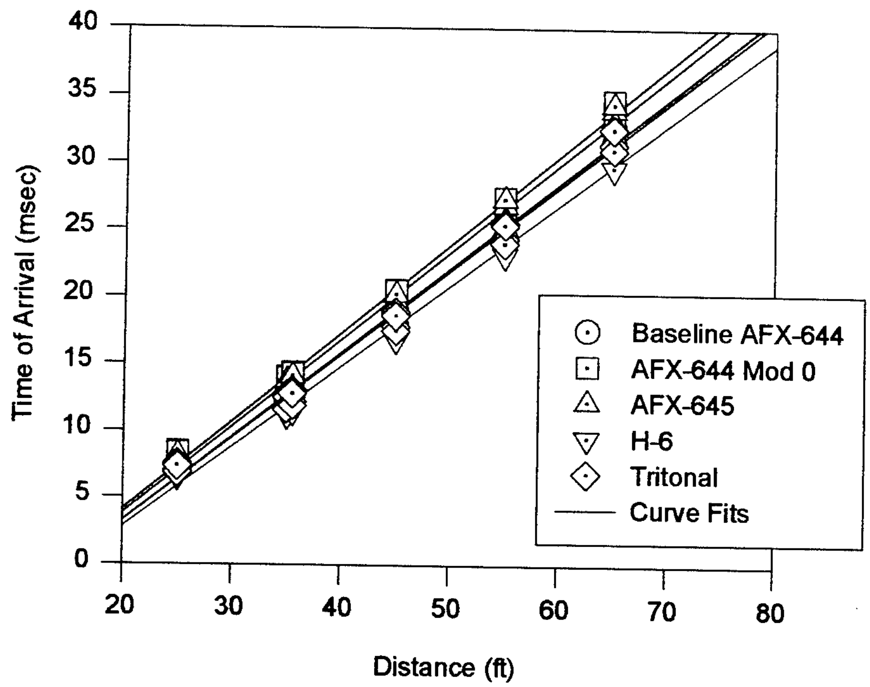

Figure 46: Blast Front Time of Arrival vs. Distance for Five Explosives in Mk-82 Bombs

Figure 47 displays the logarithmic scaled plot of peak pressure versus gauge location. It too is a good method of ranking the relative power of an explosive. However, with these data, the gauges are often sent into resonance after the initial positive pressure pulse passes and the associated ringing makes it difficult to determine the exact peak. The 'goodness' of the curve fits thus drops from an average of 0.99 as was seen in the first plot to an average of 0.93. The relative ranking from this measure of performance is: H-6 and baseline AFX-644 tied for first, then tritonal, then AFX-645 then AFX-644 Mod 0.

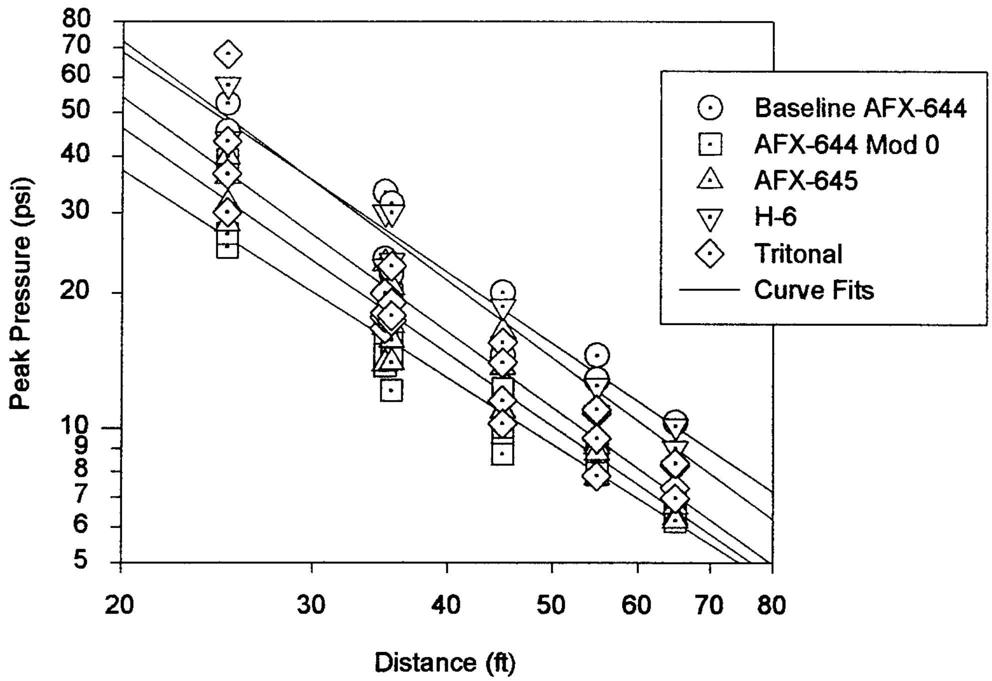

Figure 47: Blast Peak Pressure vs. Distance for Five Explosives in Mk-82 Bombs

The shock wave expanding out from the Mk-82 bomb is a positive pressure followed by a negative pressure pulse. The integration of the positive pulse with time yields an impulse value which is another good performance parameter. This integration inherently eliminates uncertainty from gauge ringing but has a different uncertainty as the pressure gauge calibration is often affected by the shock event. Best judgment is used to determine if the pre- or post-shot calibrations are used to read the results. The goodness of the curve fits for the data plotted in figure 48 average 0.83. This parameter ranks the baseline AFX-644 as the most powerful with the remainder ranked as before. It should be noted that all the data presented in figures 46-48 is a quite close ranking in that they are all nearly the same in performance. The sample size for this data is very low: two bombs each with two rows of pressure gauges. A summary comparison of the data obtained for the formulations tested ratioed with that obtained for tritonal is provided in Table XII below. The ratios presented in Table XII were calculated by ratioing the results from each of the 12 gauges and then bulk averaging these results.

Table XII: Mk-82 Performance Comparison with Tritonal

Parameter	H-6	Baseline AFX-644	AFX-644 Mod 0	AFX-645
Detonation Velocity	1.11	0.97	0.99	1.01
Peak Pressure	1.33±0.14	1.40±0.18	0.82±0.07	0.92±0.09
Impulse	1.15±0.12	1.13±0.19	0.87±0.10	0.85±0.07
Time of Arrival	1.06±0.02	0.99±0.01	0.91±0.02	0.93±0.02
Positive Phase Duration	1.10±0.13	1.06±0.09	0.98±0.05	1.00±0.08
Fragment Velocity				0.95*

* Compared to old test data

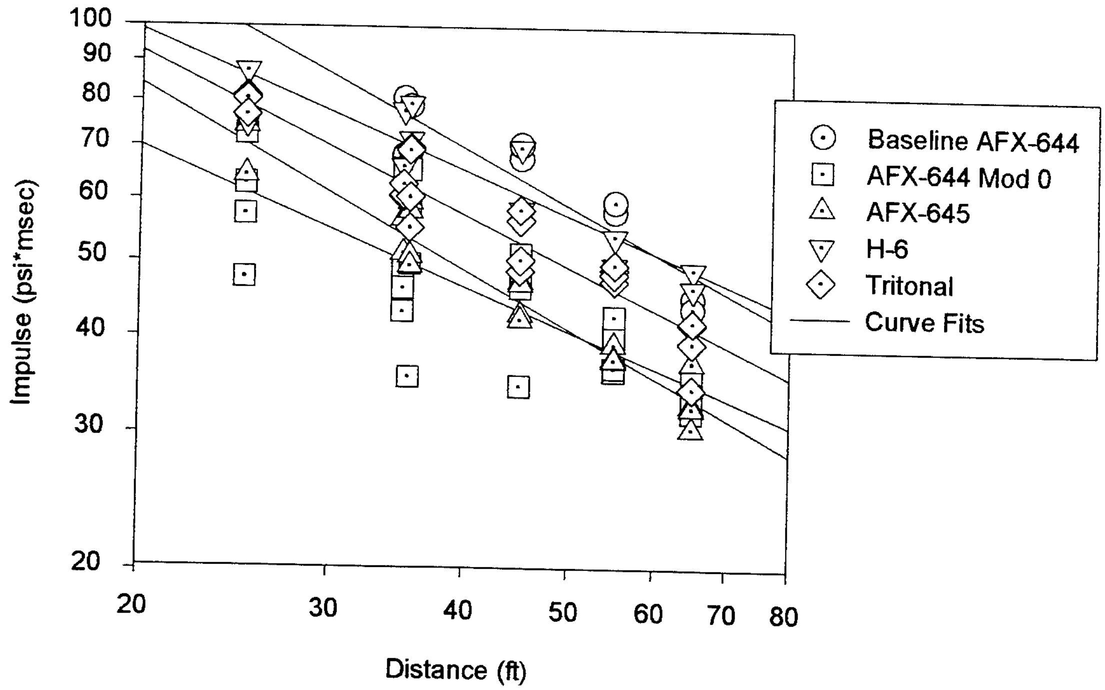

Figure 48: Blast Impulse vs. Distance for Five Explosives in Mk-82 Bombs

4.4 AFX-644 Second Reformulation Sympathetic Detonation Tests

4.4.1 AFX-645 (2-Body) Sympathetic Detonation Test

A full-scale (MK-82) sympathetic detonation test of AFX-645 (TNT/NTO/I-800 Ganex/Al-32/48/8/8/12) was conducted. The detonation of the donor bomb did not propagate to the single, live acceptor bomb. The donor bomb was placed in the bottom, center position of the new standard metal pallet between two inert BDU-50s. The acceptor bomb was placed in one of the outer columns of bombs, above one of the BDU-50s on the bottom row. The other two positions of the top row were filled with BDU-50s as well. The donor bomb had an explosive weight of 189.8 lb. and a charge density of 1.66 g/cc (95.6% TMD). The acceptor bomb had an explosive weight of 185.7 lb. and a charge density of 1.61 g/cc (92.8% TMD). The assembled pallet was positioned above a 6 ft. x 6 ft. x 1 in. steel armor plate to obtain signatures from the donor fragments as well as any generated by the acceptor bomb. A second armor plate (12 ft x 12 ft x 1 in.) was placed upright on the same side of the pallet as the live acceptor bomb at a distance of approximately 6 feet from the center of the pallet to obtain signatures from the live acceptor bomb in the event of a detonation (Figure 49). The donor bomb was initiated using 2.5 lb. of C-4. The inert acceptor bombs were stamped with letters for easy identification after the test. The bomb next to the donor and beneath the acceptor was labeled as item "T." The item directly above the donor bomb was labeled as item "A." The bomb on the other side of the donor bomb was item "C." The last bomb was item "B." The live acceptor bomb was not stamped.

A large projectile was seen departing the test site on the side of the live acceptor bomb after the detonation of the donor bomb. Upon returning downrange, EOD personnel discovered smoking remnants from the test at various points surrounding the arena. The debris from the test was recovered to assess the results of the test. The bottom witness plate was heavily scarred and cracked from the detonation of the donor bomb. The signature was very symmetrical to the center point of the armor plate, spanning 18 inches on either side of the crack. The scarring on the side witness plate was minimal except for "peppering" from small donor fragments along with a few larger impacts. No perforations were observed in this plate (Figure 50).

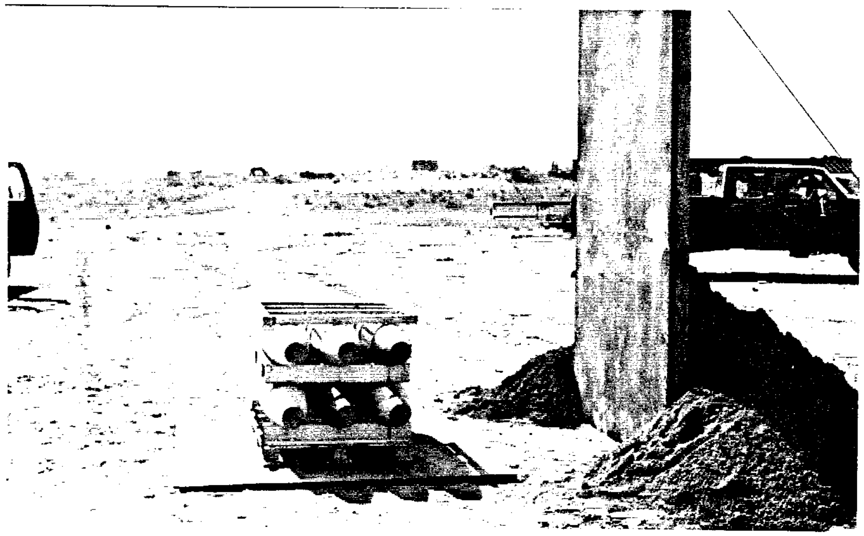

Figure 49: Two Live Body AFX 645 Sympathetic Detonation Test Set Up

Figure 50: Side Witness Plate from Two Live Body AFX-645 Sympathetic Detonation Test

Two large, unlabeled case remnants with impact signatures resembling those observed on items recovered from corner (diagonal) acceptors in previous tests were collected (Figure 51). This and other post test evidence was sufficient to determine the fate of the live acceptor in this two-body experiment. The case remnants recovered from the inert acceptor bombs were small relative to the whole bombs recovered from tests with the AFX-644 Mod 0. Qualitatively, the performance of AFX-645 was judged to be greater than that of AFX-644 Mod 0.

Figure 51: Diagonal Acceptor from Two Live Body AFX-645 Sympathetic Detonation Test

4.4.2 AFX-645 Sympathetic Detonation Test 2

A full-scale (MK-82) sympathetic detonation test of AFX-645 (TNT/NTO/I-800 Ganex/Al-32/48/8/8/12) was conducted. All of the bombs in the standard metal pallet were filled with explosive. There was no evidence of detonation from four of the five acceptor bombs; however, the fifth item reacted violently or partially detonated after a substantial run-up. The results of this test are considered as a positive indication of the low vulnerability of this formulation.

The donor bomb was placed in the bottom, center position of a standard metal pallet It had a net explosive weight (NEW) of 189.3 lb., resulting in a charge density of 1.68 g/cc (96.2 % TMD). The donor bomb was placed next to a bomb with a NEW of 187.5 lb. and a charge density of 1.63 g/cc (93.6% TMD). This adjacent bomb was labeled as item "&." The acceptor bomb on the other side of the donor bomb had a NEW of 188.2 lb. with a charge density of 1.65 g/cc (94.8% TMD). This bomb was labeled as item "A." The acceptor bomb above the donor bomb, in the top, center position of the pallet had an explosive weight of 186.2 lb. with charge density was 1.63 g/cc (93.8% TMD). This bomb was labeled as item "B." The bomb above item "&" was labeled as item "P." It had an explosive weight of 186.5 lb. with a charge density of 1.62 g/cc (93.2% TMD). The bomb above item "A" was labeled as item "K." It had an explosive weight of 185.8 lb. with a charge density of 1.66 g/cc (95.3% TMD). The assembled pallet was positioned on a 6ft. x 6ft. x 1 in. steel armor plate to obtain signatures from the donor fragments as well as any generated by the acceptor bombs. An identical witness plate was placed above the pallet at a height of 6 feet. It was covered with sandbags and supported on a wooden stand. Vertical armor plates (12 ft x 12 ft x 1 in.) were placed upright on both sides of the pallet at a distance of approximately 6 feet from the center of the pallet to obtain signatures from the acceptor bombs in the event of a detonation. The donor bomb was initiated using 2.5 lb. of C-4 and a blasting cap fired from a non-electric timed fuze.

The bottom witness plate was heavily scarred and cracked from the detonation of the donor bomb. A 1 ft by 2 ft section of the plate was removed from the main remnant of the plate in the center region of the plate where the bomb tails originally resided. The signature from the donor detonation was very symmetrical to the center point of the armor plate, spanning 17 inches on either side of the crack. Besides this donor scarring, a few fragment markings were observed beyond the original position of item "A." They were isolated to the last 21 inches of plate in the region originally covered by the tails of the bombs (Figure 52). The side witness plates were recovered at a distance approximately 100 yards beyond the edge of the arena. Both plates were bent severely by the impact of the diagonally positioned acceptor bombs as they were accelerated by the detonation of the donor bomb. The scarring on the side witness plate closest to items "P" and "&" was minimal except for "peppering" from small donor fragments along with one perforation (Figure 53 Left). The plate was deformed (folded) with a crease at approximately 65 inches from the bottom of the plate. The side witness plate closest to items "K" and "A" (Figure 53 Right) showed heavy scarring below the crease at 60 inches from the bottom of the plate, in the region spanning the half of the plate corresponding to the original tail position of item "A." Ten perforations were evident in this region. The top witness plate (Figure 54) was deformed due to the mechanical impact of the top center bomb as it was accelerated by the donor detonation. Also, there was one perforation and a few fragment impacts in the region of the top plate originally positioned above the tail region of items "K" and "A."

Figure 52: Bottom Witness Plate from 6 Live Bomb AFX-645 Sympathetic Detonation Test

Positively identifiable case remnants were recovered from all of the test items. Substantial pieces of the nose sections were recovered for all of the items originally positioned on the top row of the pallet. Approximately one third of the case from the top, center item (B Figure 55) was recovered as a single piece. The nose sections of items "P" (Figure 56) and "K" (Figure 57) were severely scarred by fragment impacts from the donor bomb. Other remnants from these items exhibited the severe impact and flow-like characteristics typical of the region directly impacted by the prematurely fractured donor bomb fragments as well as those reflected from the items adjacent to the donor bomb. Numerous large, plate-like pieces were recovered from item "&." (Figure 58). Fewer of these type of fragments were recovered for item "A" (Figure 59). Some unreacted melt-cast type explosive was recovered near some of the recovered case pieces, but its origin could not be positively identified.

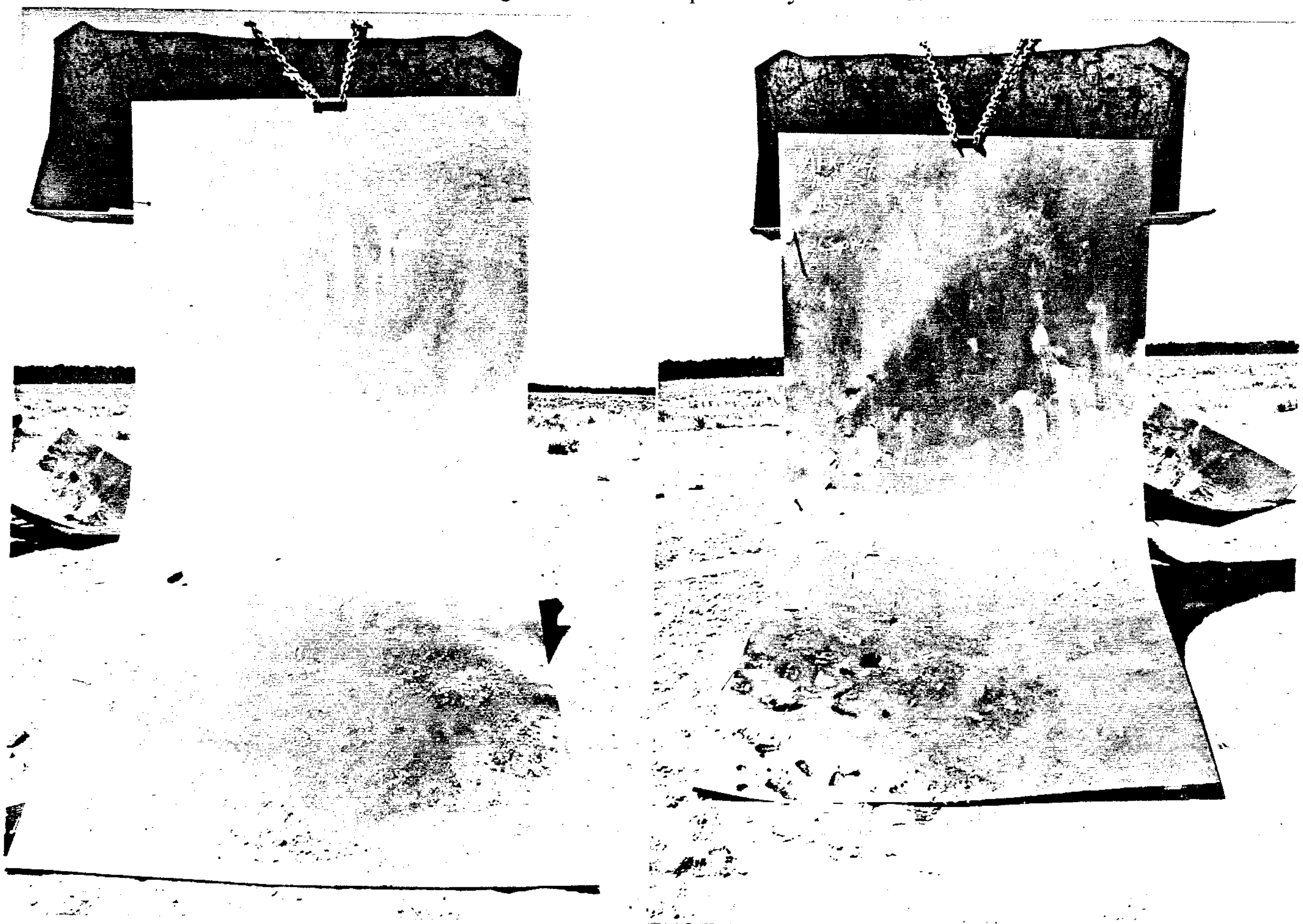

Figure 53: '&' and 'A' Side Witness Plates from 6 Live Bomb AFX-645 Sympathetic Detonation Test

The evidence from this test reveals that four of the five acceptors in this test did not react violently or detonate. These included both of the diagonally positioned items. One of the items adjacent to the donor bomb ("A") did result in a non-prompt, violent reaction or a partial detonation. However, the energy emitted by this reaction was not substantial enough (or prompt enough) to propagate a reaction in its nearest neighbor bomb, item "K," (which was originally positioned diagonally with respect to the donor bomb).

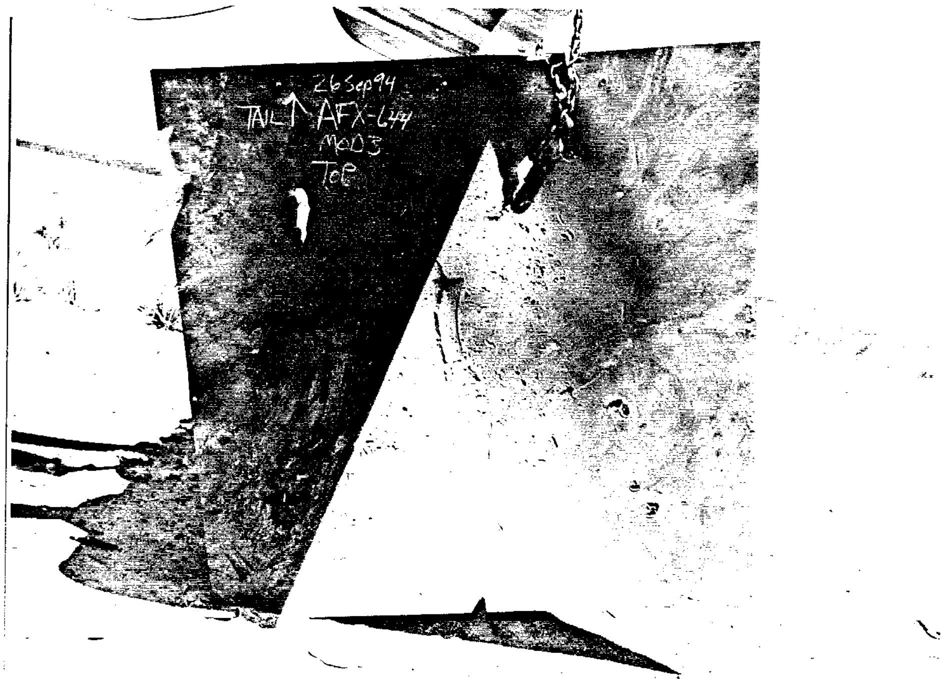

Figure 54: Top Witness Plate from 6 Live Bomb AFX-645 Sympathetic Detonation Test

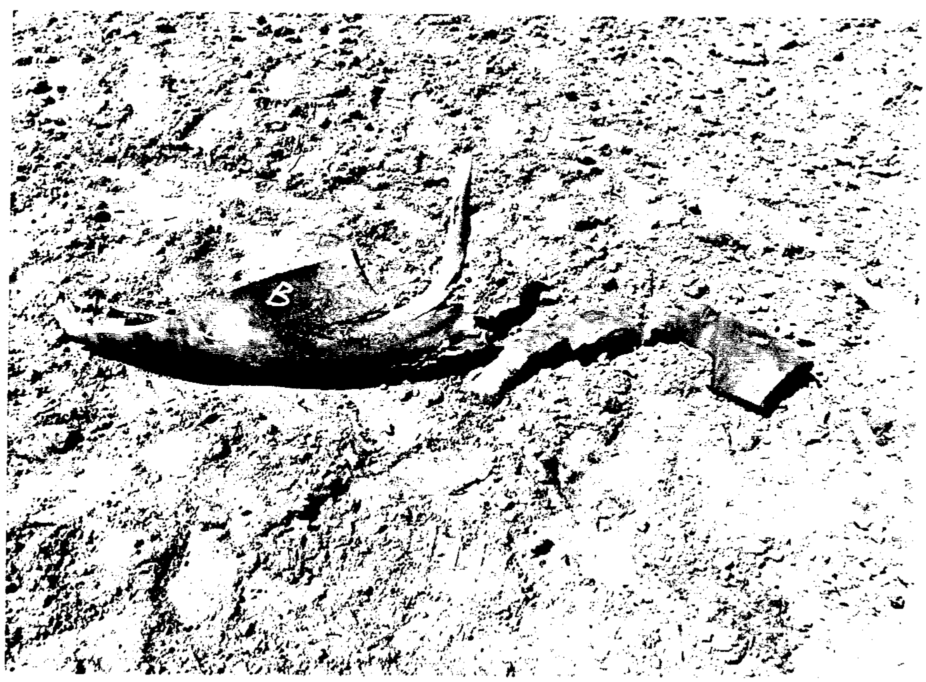

Figure 55: Top 'B' Acceptor from 6 Live Bomb AFX-645 Sympathetic Detonation Test

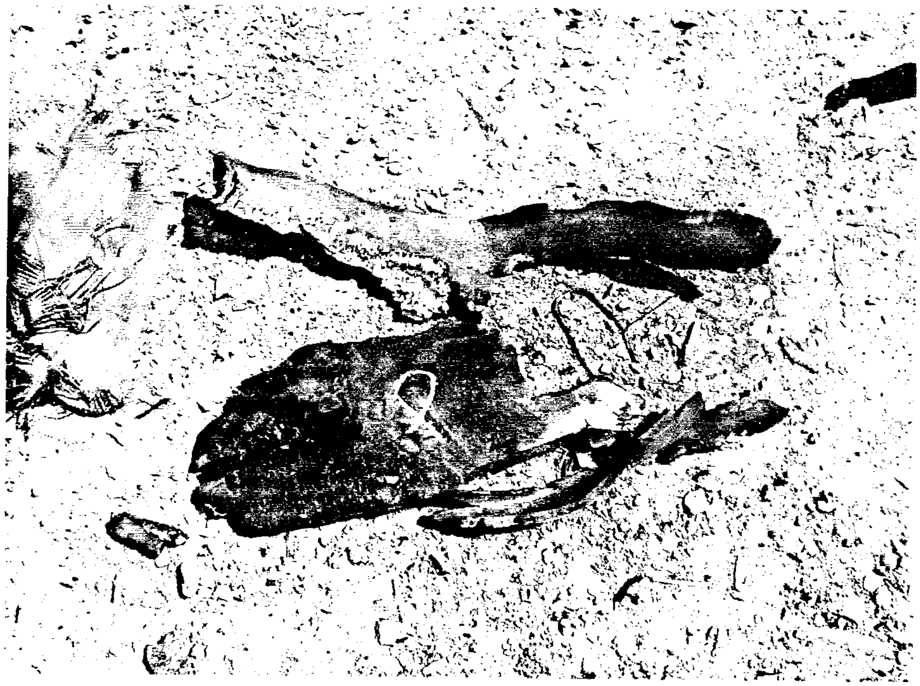

Figure 56: Diagonal 'P' Acceptor from 6 Live Bomb AFX-645 Sympathetic Detonation Test

Figure 57: Diagonal 'K' Acceptor from 6 Live Bomb AFX-645 Sympathetic Detonation Test

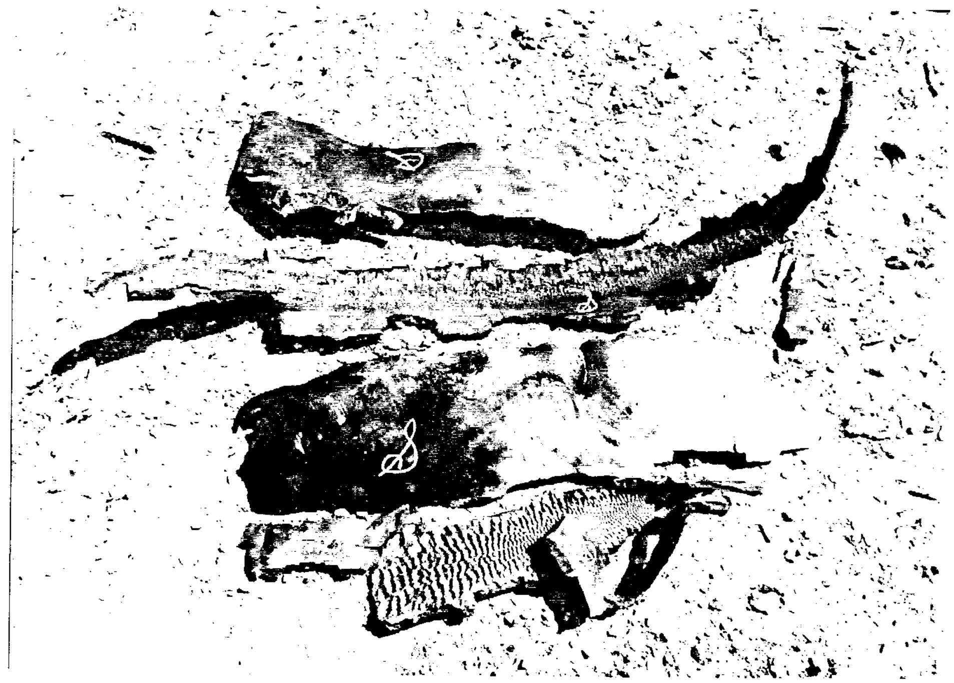

Figure 58: Adjacent '&' Acceptor from 6 Live Bomb AFX-645 Sympathetic Detonation Test

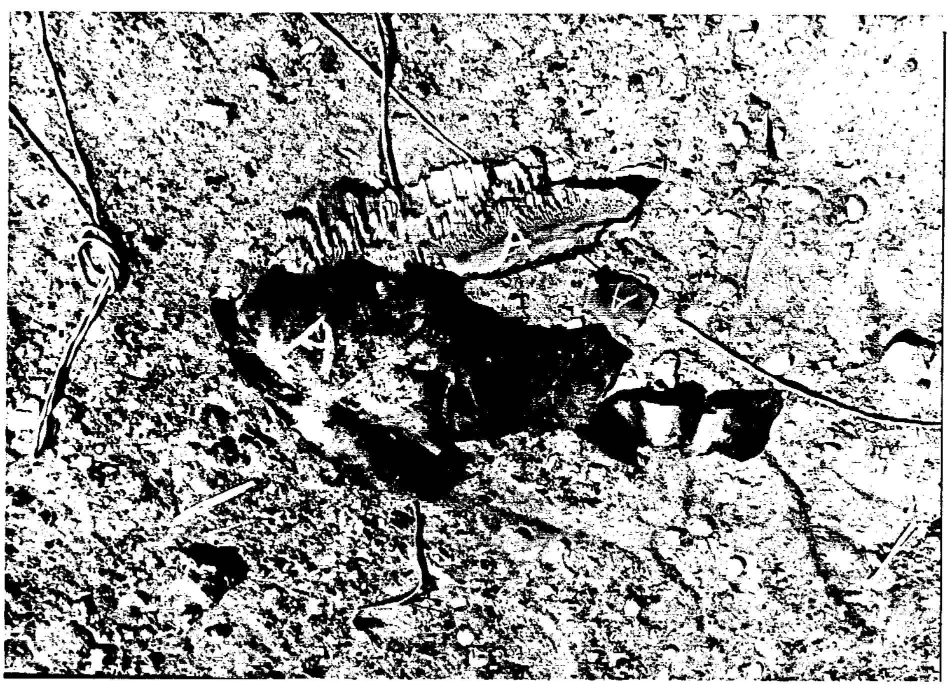

Figure 59: Adjacent 'A' Acceptor from 6 Live Bomb AFX-645 Sympathetic Detonation Test

Section Five: Initiation System for the Fuzed Insensitive General Purpose Bomb

5.1 Strategy For Boostering Tests and Fuze Hardware

The program goals included the demonstration of advanced insensitive high explosive (IHE) technology in an existing weapon system. An objective was to use the FMU-139 fuze with as few modifications as possible to detonate the IHE. The strategy for achieving this was to first determine the booster size and material needed to detonate the AFX-644 and then determine the best fuze configuration to house this booster. This strategy was followed by first testing several inventory boosters against the IHE. After these tests proved unproductive, a booster material was chosen such that it could be stored in the weapon if needed and maintain the desired 1.6 hazard classification. A series of tests, supplemented with hydrocode modeling were performed to size this booster. This was followed by a series of detonation tests of this insensitive booster material to size and select a lead material and configuration. The fuze hardware was examined to configure a system which would be compatible with the FMU-139 fuze. These steps are explained in greater detail in the following sections and are summarized in Table XIII.

Concurrent with this program, a contracted effort with AAI Corp. of Hunt Valley, MD called Insensitive Munition Fuze Technology (IMFT) produced a fuze which was tested against AFX-644. This program is fully described in References 13 and 14. The layout of that explosive train and a summary of its characteristics is included below for completeness. Not coincidentally, the IMFT explosive train is very similar to the modified FMU-139 explosive train developed in this program.

Most of the boostering tests against AFX-644 were conducted in an 8 inch diameter by 16 inch long steel can filled with the candidate explosive and employing mock fuze hardware. The IMFT booster tests were conducted with the front half of an actual Mk-82 bomb. As can be seen in Table XIII below, several versions of AFX-644 were tested. Most of the booster testing was conducted concurrent with the first reformulation effort. However, comparing the booster tests with the sensitivity tests of Table V shows that the least sensitive AFX-644 formulation, AFX-644 Mod 0, was successfully detonated by the modified FMU-139 explosive train at -67°F.

5.2 Existing Boosters

Three inventory booster designs were tested against baseline AFX-644 and the more sensitive TNTO II formulation[3] (TNT/NTO/D2/Al 32/42/7/19). It was postulated that the standard FMU-139 with an annular CH-6 booster of 125 gm would be incapable of detonating baseline AFX-644. This was proven as shown in Figures 60 and 61. The M-148 auxiliary booster with 182 gms of tetryl was tested against TNTO II successfully. The 284 gm tetryl T-147 booster was tested successfully against TNTO II and unsuccessfully against baseline AFX-644. These tests showed that no inventory booster was capable of reliably detonating the very insensitive baseline AFX-644. Two additional explosives were tested as candidate boosters: PBX-9502 and PBX-9503. In appropriate dimensions, both these explosives had sufficient power to detonate baseline AFX-644 and its modifications. PBX-9502 was selected due to its extreme insensitivity and acceptance within the weapons community. These tests further proved what had long been suspected: an annular booster would not perform well against AFX-644 due to its relatively large critical diameter. An IHE with a large critical diameter is more easily detonated with a cylindrical 'end light' boosting scheme. The toroidal booster in many bomb fuzes results in a peculiar detonation front shape. The detonation front in the booster is shaped by the hole of the toroid such that the peak pressure is experienced on the side of the fuze at a point furthest away from the detonator[19].

Table XIII: Summary of AFX-644 Initiation Test Results

Test Item (Donor)	Tested Against (Acceptor)	Test Condition*	Result
FMU-139 (Annular--125g CH-6)	Baseline AFX-644	Ambient	NO GO
T-147 Auxiliary Booster (Annular 284g Tetryl)	TNTO IV (Baseline AFX-644)	-65°F	NO GO
T-147 Auxiliary Booster (Annular 284g Tetryl)	TNTO II	-65 °F	GO
PBX-9503 (Annular 500 g)	Baseline AFX-644	-65°F	GO
M-148 Auxiliary Booster (Annular 182 g Tetryl)	TNTO II	-65 °F	GO
PBX-9502 (Cylindrical 3" X 3") Flat Bottom Fuzewell	Baseline AFX-644	Ambient	GO
PBX-9503 (Cylindrical 3" X 3")	Baseline AFX-644	Ambient	GO
PBX-9502 (Cylindrical 2.7" Dia X 3")	Baseline AFX-644	-65 °F	GO
PBX-9502 (Cylindrical 2.4" Dia. X 1")	Baseline AFX-644	-58°F	NO GO
PBX-9502 (Cylindrical 2.4" Dia. X 1.875")	Baseline AFX-644	-65°F	NO GO
PBX-9502 (Cylindrical 2.4" Dia. X 2.5")	Baseline AFX-644	-65°F	GO
PBX-9502 (Domed Shape 2.4" Dia. X 2.25")	Baseline AFX-644	-65°F	GO
A5 Pellet (Cylindrical 0.5" X 0.5") Off Center	PBX-9502 (Cylinder 2.44 Dia x 3)	-65°F	LATE GO
A5 and PBX-9502 (Cylindrical 2.44" Dia. X 3")	Baseline AFX-644	-65°F	GO
PBXN-7 (Cylinder 2.44 Dia X 1) Through Metal Plate	PBX-9502	-65°F	NO GO
PBXN-7 (Cylindrical 1" X 1") with 0.01 Flyer Plate and 0.04 Air Gap	PBX-9502	-65°F	GO
PBXN-7 (Cylindrical 1" X 1") with 0.03 Flyer Plate and 0.125 Air Gap **	PBX-9502	Ambient	GO
** Modified FMU-139 and PBX-9502 Aux Booster	AFX-644 Waxless	-57°F	GO
Modified FMU-139 and PBX-9502 Aux Booster	AFX-644 4% Wax	-65°F	GO
Modified FMU-139 and PBX-9502 Aux Booster	AFX-644 Mod 0	-67°F	GO
IMFT Fuze	AFX-644 4% Wax	Ambient	GO
IMFT Fuze	AFX-644 4% Wax	-51°F	GO
IMFT Fuze with AHM on Fuzewell	AFX-644 4% Wax	-54°F	GO
IMFT Fuze in Standard Fuzewell with AHM	Tritonal	-50°F	GO

* Cold test conditions were achieved by soaking the test items until equilibrium was reached with the pre-set freezer temperature. 65 below was the goal on all cold tests. However, some tests were conducted in the heat of summer where the freezer was incapable of getting that cold.

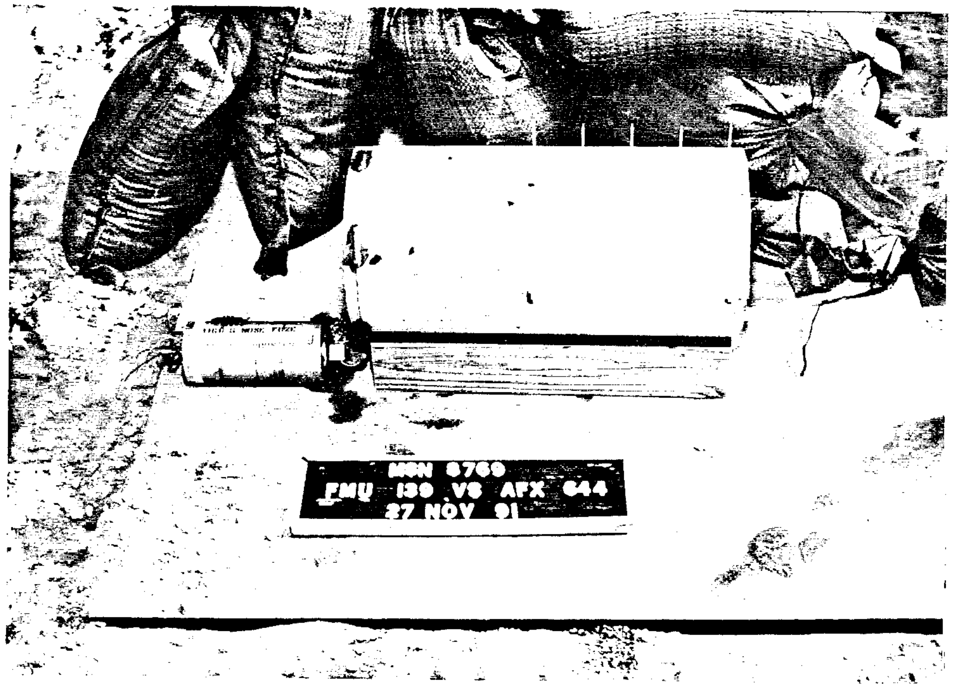

Figure 60: FMU-139 Fuze to AFX-644 Booster Test Set Up

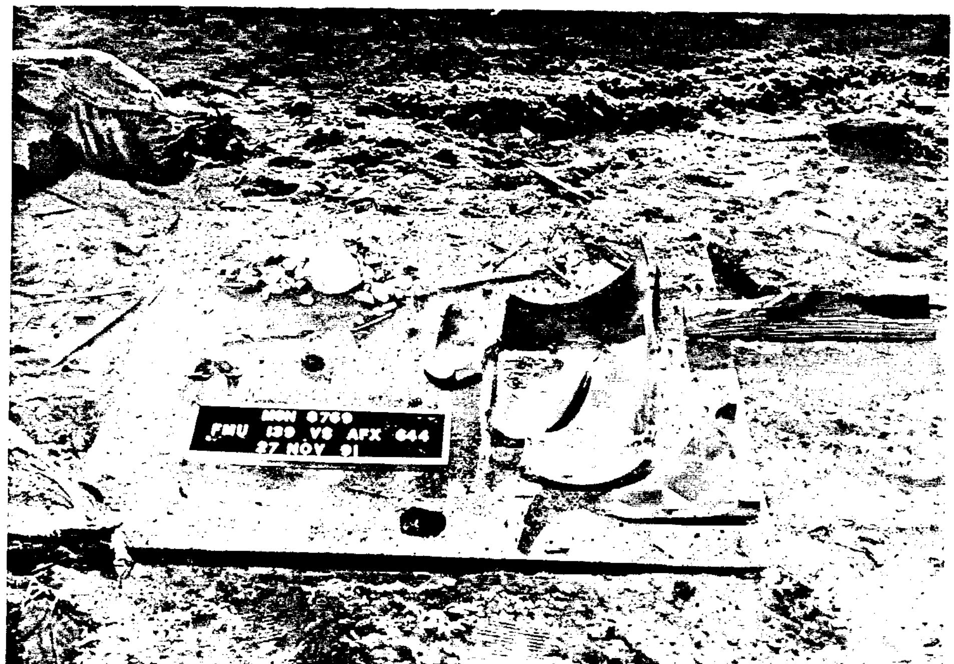

Figure 61: FMU-139 Failure to Detonate AFX-644

5.3 PBX-9502 Booster Sizing

PBX-9502 (95% TATB, 5% Kel-F) was selected as the auxiliary booster explosive due to its extreme insensitivity and demonstrated effectiveness as an initiating material. A series of five detonation tests were conducted to determine the quantity of PBX-9502 needed to reliably detonate baseline AFX-644. The diameter of booster chosen to test was 2.44 inches which corresponds to the diameter of the booster cavity in the FMU-139 fuze. Testing determined that the minimum length needed was between 2.5 and 1.875 inches. If the shape was changed to domed instead of cylindrical, a slightly smaller quantity of booster could deliver a higher peak pressure into the main charge. This was proven with hydrocodes and experiments. Hydrocode sample outputs for the 2.5 inch cylindrical and domed booster configurations are shown in Figures 62 and 63. The domed booster has several advantages which were not fully explored in this test program. The obvious advantage is that less explosive is needed and thus it provides a more elegant boostering scheme. The shape of the advancing detonation front closely matches the shape of the hardware and provides efficient energy transfer into the main charge. Another advantage is that the domed fuzewell is stronger in the axial and lateral directions. This could be a significant advantage in hard target penetration environments. Despite these advantages, cylindrical boosters of 2.44" diameter by 3.0" length were used through out the remainder of the program. This decision was made for ease of machining hardware; the 3.0" length provided some design margin.

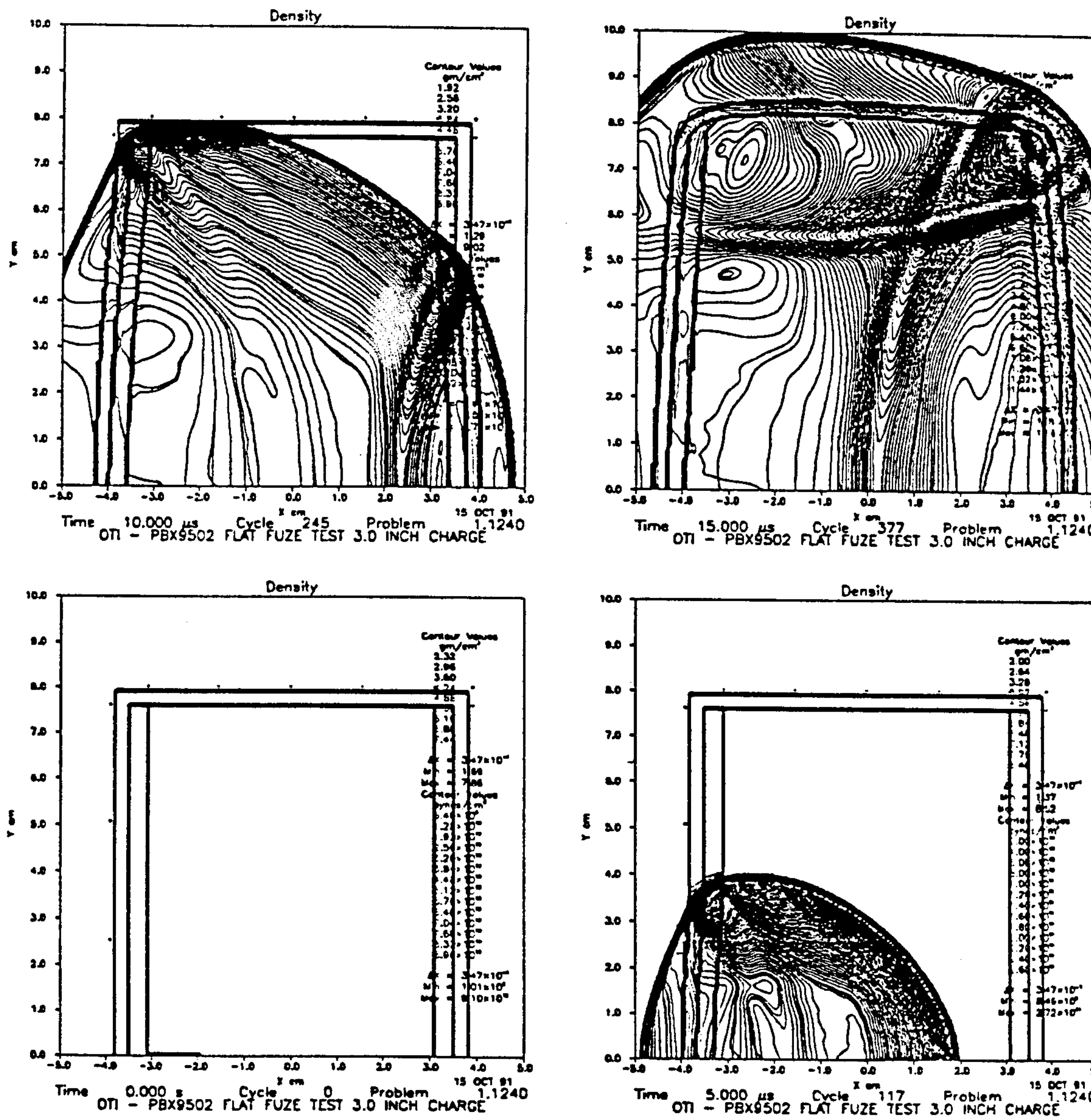

Figure 62: Hydrocode Output 2.44 Dia. by 2.5 Cylindrical Booster

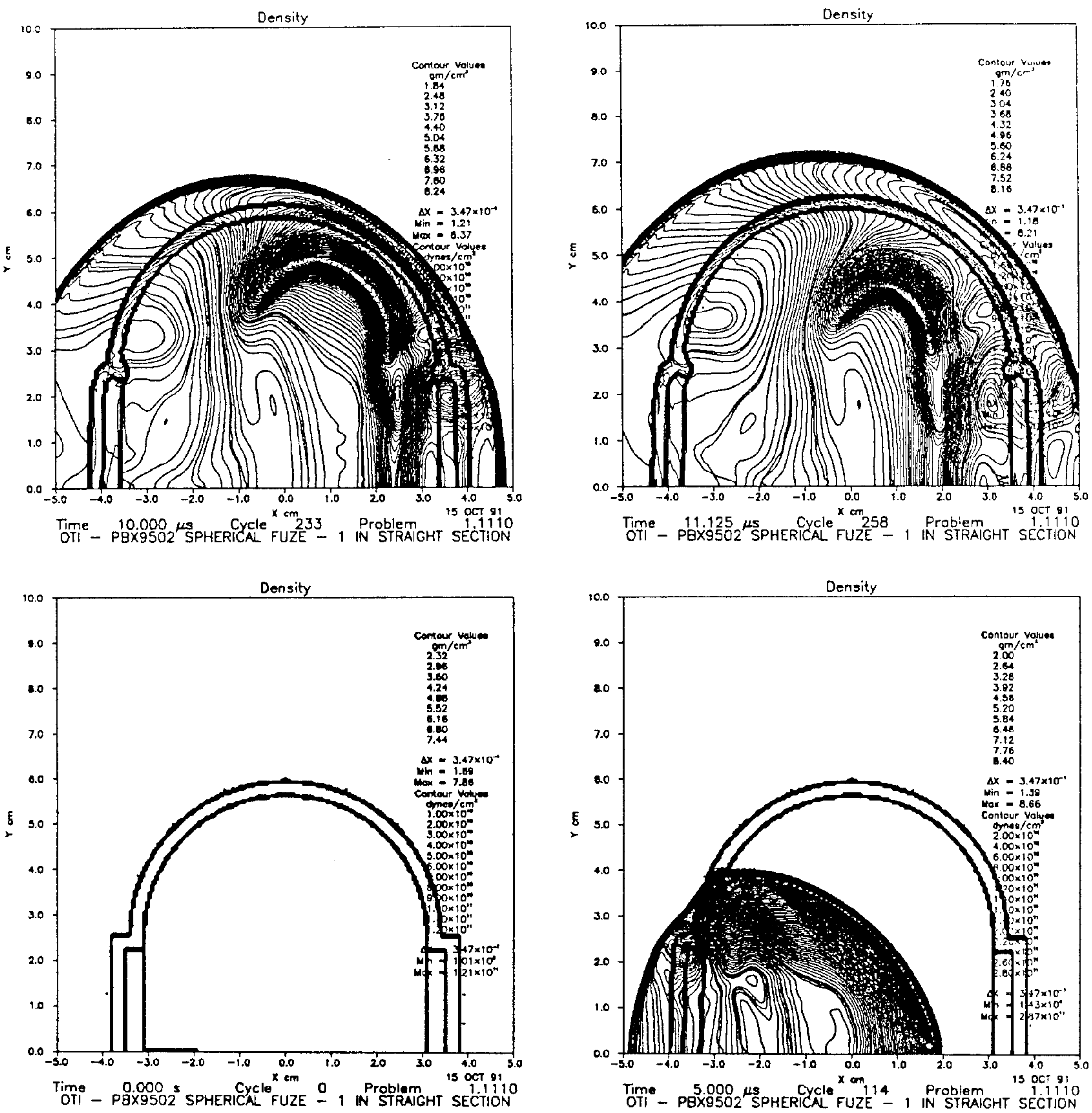

Figure 63: Hydrocode Output 2.44 Dia. by 2.25 Domed Booster

The booster testing was conducted in an 8 inch diameter by 16 inch long steel can called an engineering scale unit which was usually conditioned to -65°F (Figure 60 and Figure 64). The instrumentation included piezoelectric time-of-arrival (TOA) pins to measure shock and/or detonation velocity as well as armor witness plates to determine No Go or Go (Figure 65).

Figure 64: Engineering Scale Unit for Booster Test Conditioned to -65°F

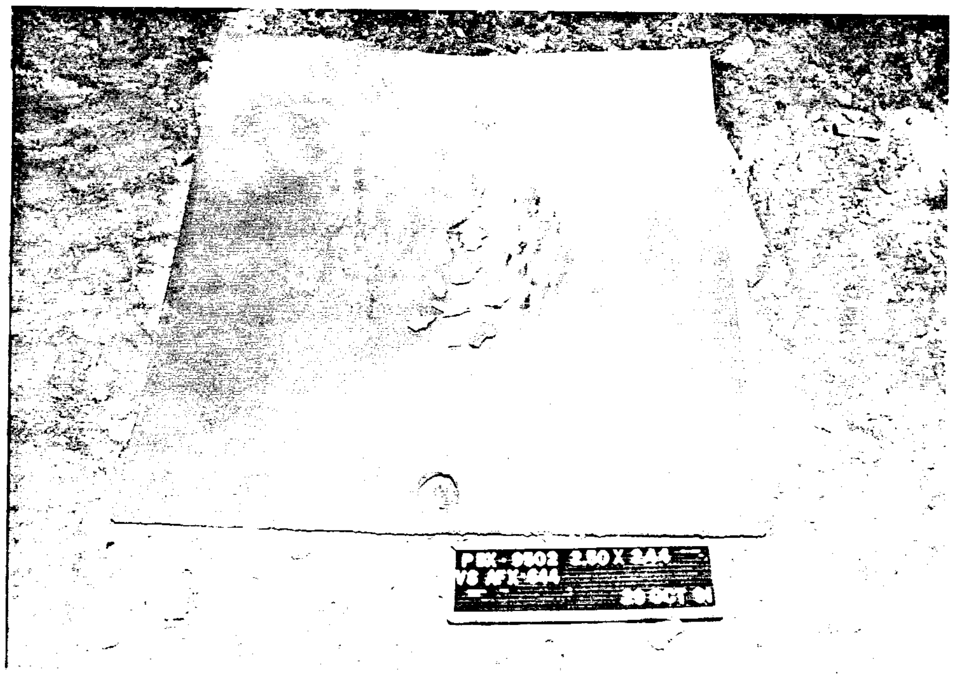
Figure 65: Witness Plate and Fragments for a Prompt Detonation

5.4 Critical Diameter Testing

Conical charges were used to estimate the critical diameter of baseline AFX-644 and AFX-644 Mod 0[15]. The cones tapered from an initial diameter of 4 inches to a final diameter of 1 inch. The base of the cones were 4-inch diameter x 4-inch long cylinders of the formulation being tested. This base was initiated using 4-inch diameter x 4-inch long cylinder of Comp B. Piezoelectric pins were positioned at intervals of 30 mm to determine the velocity of the reaction wave as it propagated through the cone. The critical diameter is the diameter at which the velocity of the reaction wave measured in the cone is 90% of the detonation velocity measured in the cylindrical base of the cone. One cone of each formulation was tested. The results are presented in Table XIV.

Table XIV: Critical Diameters of AFX-644 Variations Determined from Cones

Parameter	Density	D_C
Baseline AFX-644	1.72 g/cm^3	33-39 mm
Baseline AFX-644	1.70 g/cm^3	41-43 mm
AFX-644 Mod 0 *	1.65 g/cm^3	44-49 mm

* 9.5% I-800, 0.5% Ganex WP-660 vs.
9.85% I-800, 0.15 Ganex WP-660 in final formulation

5.5 Lead Sizing

PBX-9502 requires a larger diameter fuze lead than the Mk-8 found in the FMU-139 to accommodate its larger critical diameter. A 0.5" Dia. X 0.5" cylindrical pellet of A5 explosive proved capable of detonating the booster at -65° F. However, the TOA pin data from this test indicated that the detonation in the PBX-9502 was still accelerating at the end of the booster. To ensure that this 'late' detonation was adequate, this whole explosive train was tested against baseline AFX-644 at -65° F. This test was a clear 'Go'. At this point the explosive train, configured as a large booster inside a redesigned fuze, was judged to be excessively long. It was decided to change the configuration to that of an auxiliary booster which would remain with the bomb and to use a small booster in the FMU-139 which would permit relatively simple fuze hardware modifications. The PBX-9502 auxiliary booster was, from this point onward, placed at the bottom of a long flat bottomed fuzewell and covered with a 0.005" stainless steel cover as a weather seal (Figure 69).

PBXN-7 explosive material was chosen to supplement the FMU-139 detonator and lead. This explosive was chosen as it is a qualified material in use with several fuzes. Furthermore, this explosive does pass cook-off tests although it is too shock sensitive to meet the 1.6 hazard classification criteria. The first test of this material proved that even a large quantity of it could not detonate the PBX-9502 with a metal attenuator between it and the booster. Lessons learned from other detonation transfer problems suggested that if a layer of metal is impeding detonation, that metal should be made to fly across an air gap to enhance detonation reliability. The next configuration tested had a much smaller PBXN-7 lead (23 g instead of 137 g) which accelerated a 0.010 inch thick 0.875" diameter steel plate across an 0.040 inch air gap. HULL hydrocode modeling suggested that this scheme would fail to transfer detonation at -65° F yet the test did prove to be a 'Go'. The flyer plate boosting scheme for the auxiliary booster was explored numerically in greater detail with the SMERF code as described below. The dimensions of the flyer and air gap were tripled to 0.030 inch and 0.125 inch, respectively. Modeling suggested higher shock pressures and longer duration pulses into the booster with this configuration. The 0.125 inch air gap is much easier to achieve and less tolerance sensitive in representative hardware assembly. This 'flyer plate' boosting scheme formed the basis of the FMU-139 and Mk-82 bomb modifications in this program.

5.6 SMERF Simulation of the FIGPB Flyer Plate Initiation System

Hydrocode calculations employing Software for Multi-Eulerian Reactive Flow (SMERF) were performed by Brumback and Woo[16] to determine the effectiveness of the flyer plate design for initiating PBX-9502. In these calculations, a PBXN-7 booster was initiated, launching a steel flyer plate across an air gap and into a steel plate which covers the PBX-9502 auxiliary booster. Pressure nodes for the calculations were placed along the path of the shock front in the various materials. An illustration of the flyer plate initiation train is provided in Figure 66. In the calculations, the air gap thickness and the flyer plate thickness were varied independently to determine which combination was most effective in detonating the PBX-9502 auxiliary booster. The cover plate thickness was constant at 0.005 inches.

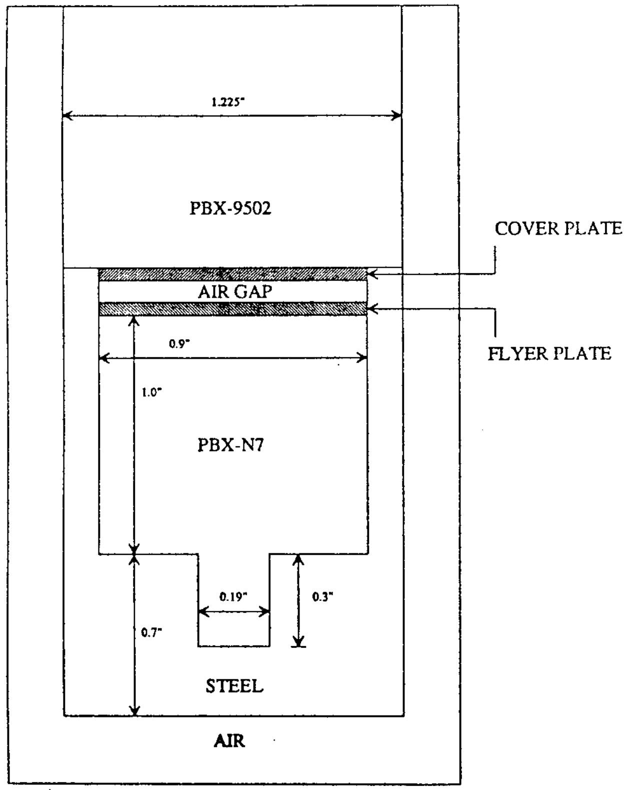

Figure 66: Flyer Plate Initiation Train as Simulated in SMERF Calculations

The hydrocode calculations confirmed that all sixteen combinations of the thicknesses are effective at sustaining a detonation in the PBX-9502 auxiliary booster. The detonation wave determined in the calculations is presented in Figure 67 for a flyer plate thickness of 0.030 inches and an air gap thickness of 0.125 inches. The maximum flyer plate velocity calculated for each plate/gap thickness combination and the maximum pressure generated in the PBX-9502 auxiliary booster for each plate/gap thickness combination are provided in Table XV.

Table XV: Maximum Flyer Plate Velocity and Pressure in the PBX-9502

Flyer Plate Thickness (inches)	Air Gap Thickness (inches)			
	0.04	**0.08**	**0.10**	**0.125**
0.01	3.2 km/s 346 kbar	3.6 km/s 368 kbar	3.8 km/s 379 kbar	3.9 km/s 379 kbar
0.02	2.4 km/s 335 kbar	2.9 km/s 371 kbar	3.0 km/s 371 kbar	3.1 km/s 369 kbar
0.03	2.1 km/s 351 kbar	2.5 km/s 370 kbar	2.6 km/s 359 kbar	**2.7 km/s** **352 kbar**
0.04	1.9 km/s 252 kbar	2.2 km/s 352 kbar	2.3 km/s 368 kbar	2.5 km/s 355 kbar

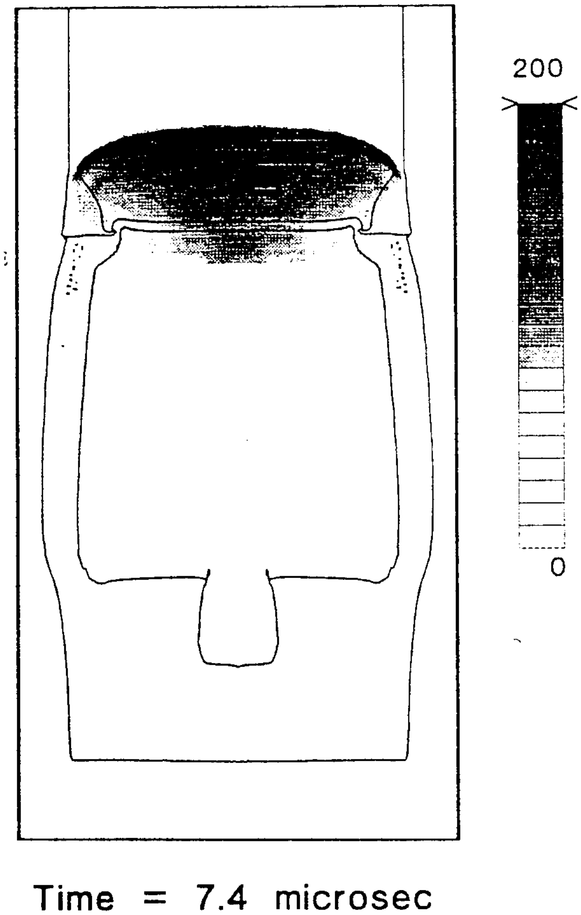

Figure 67: SMERF Results of 0.030 Flyer and 0.125 Air Gap

5.7 FMU-139 Modifications

The initiation train for the FIGPB is derived from the FMU-139 fuze which, at program start, had only recently entered the munitions inventory. The electronic safe/arm mechanism, rotor, detonator and lead were not changed in this program. However, the new configuration is required to initiate reliably less sensitive explosives having larger critical diameters and initiation pressures than the current bomb fills. Specifically, the output from the booster explosive must be greater than the initiation pressure of the main charge explosive when the generated shock wave grows to the critical diameter of the main charge explosive. The standard fuze configuration with the electrical connector entering the center of the fuze through the hole in the booster requires a series of plates, pads and structural features to support the charging tube and protect the booster. These pieces mitigate the pressure output from the CH-6 or PBXN-7 booster before the pressure pulse reaches the main charge explosive.

The re-design of the FMU-139 involved replacement of the annular CH-6 booster with a smaller, cylindrical PBXN-7 'flyer plate' lead. The large solid cylindrical PBX-9502 auxiliary booster requires the relocation of the fuze electrical connector to the face plate of the fuze at the rear of the bomb. This has some structural advantages and vastly improves the shock impedance matching between the booster and the main charge. The modified FMU-139 is shown in Figure 68. This figure shows the cavity for the 1.0 inch diameter cylindrical PBXN-7 booster and the new bottom plate of the fuze with a recessed area which forms the flyer plate.

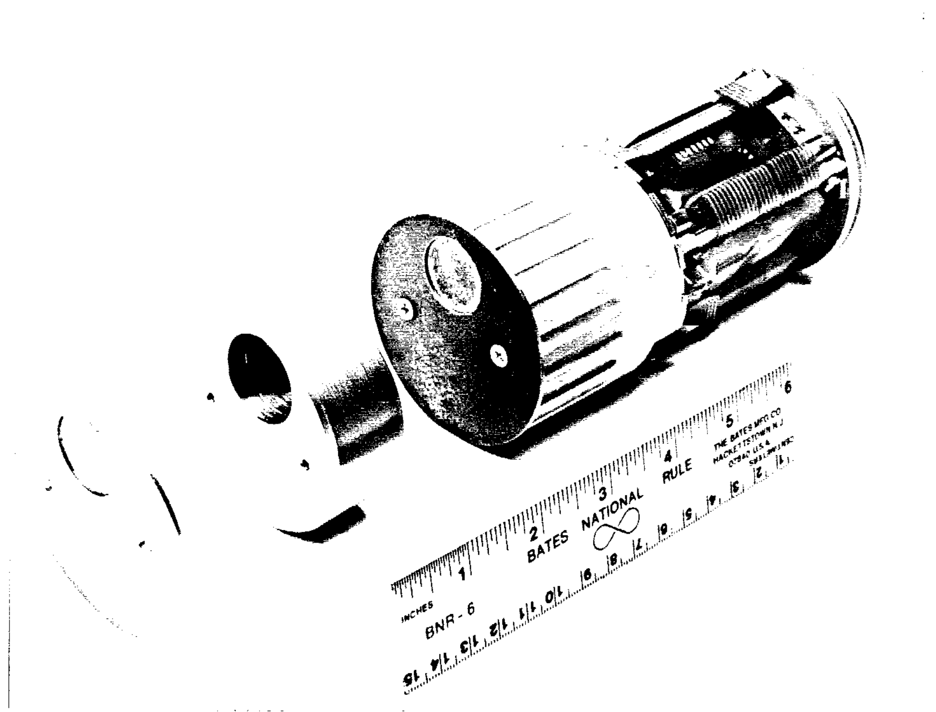

Figure 68: 'Flyer Plate' modified FMU-139

5.8 Bomb Modifications

The bomb's rear internal charging tube must be moved such that it tunnels from the charging well to the aft closure of the bomb. Prototype versions of a modified Mk-82 bomb aft closure have been fabricated. The aft closure is removed from the standard Mk-82 bomb and the new aft closure is welded on allowing the charging tube to exit the tail of the bomb beside the fuzewell (Figure 69). Explosive loading with this bomb is accomplished by filling the bomb through the large hole in the aft closure to a predetermined level and then inserting the new fuzewell into the molten explosive and attaching it to the aft closure with a screw locking ring. The fuzewell with auxiliary booster already installed is pre-heated to 80°C prior to insertion. The liquid explosive is displaced by the fuzewell upon insertion. The procedure allows for the inspection and cleaning of the aft closure prior to inserting and locking the new fuzewell. This ensures that no explosive is present in the area of the threads. The item is capped off with a "tuff seal" pad by injecting this fluid through ports in the aft closure. These ports are then filled by threaded bolts. This procedure is considered easier than that used for standard bombs where the rear fuzewell must be pushed aside inside the case then repositioned after filling and re-attached to the aft closure. The modified bomb is robust enough to accommodate fuze designs up to 4.0 inches in diameter, allowing custom initiation schemes for various explosive fills possessing different critical diameters and initiation pressures. No special bomb venting features were built into this aft closure. The results of some of the fast cook-off tests indicated that such a feature would be desirable. Schemes for modifying the aft closure of a large weapon to provide venting have been investigated by NAWC China Lake[17].

A new fuzewell was built and tested. It has a 2.44 inch diameter by 3.0 inch long cavity at the bottom for the PBX-9502 auxiliary booster and a larger cavity for the modified FMU-139 (Figure 70). Once the PBX-9502 booster is inserted, it is covered by a thin (0.005 inch) stainless steel shim stock to provide a weather seal. This is done before the fuzewell is inserted in the bomb. The step change in inside diameter provides a load path for the mass of the fuze during bomb impact. The weight of the fuze does not bear on the auxiliary booster. The thickness of the end of the fuzewell and the sides surrounding the booster was made to be the same as conventional fuzewells (0.040 inch) so as to provide a standard detonation impedance. The thickness of the side wall in the vicinity of the fuze was made thicker (0.070 inch) to provide better load carrying capacity. Detailed strength analysis of this fuzewell was not carried out. Should such an analysis prove that more strength is needed, the side wall thickness of both cross sections can be increased without any effect on the detonation transfer reliability as this explosive train couples energy primarily through the bottom of the fuzewell. No asphaltic hot-melt liner (AHM) was used on these fuzewells although later tests with the critical module proved that such a liner would not prevent detonation of the main charge.

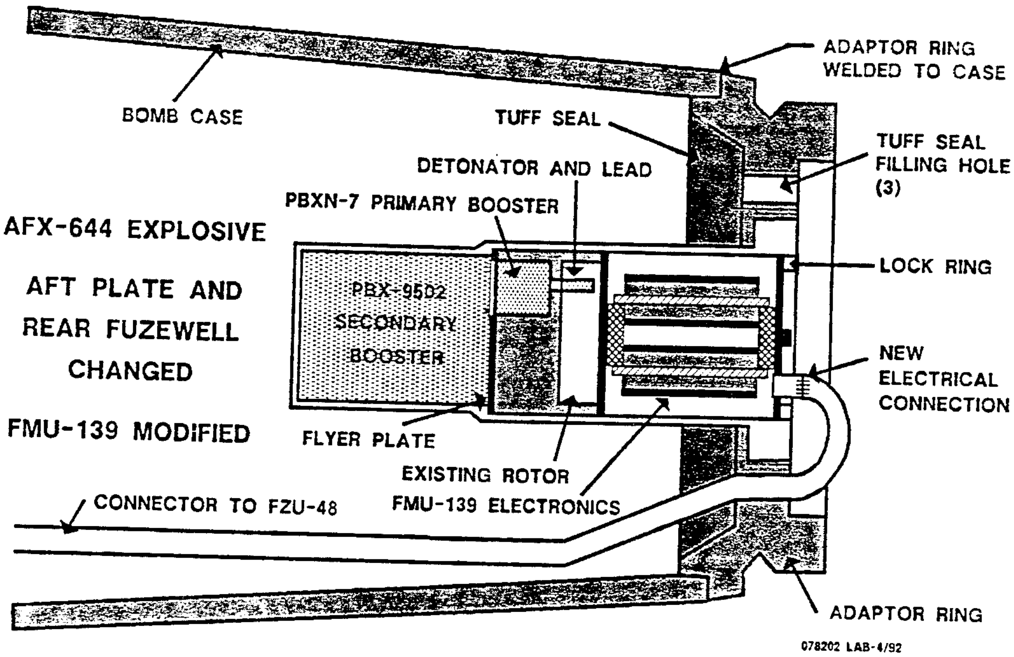

Figure 69: Mk-82 Bomb Modifications.

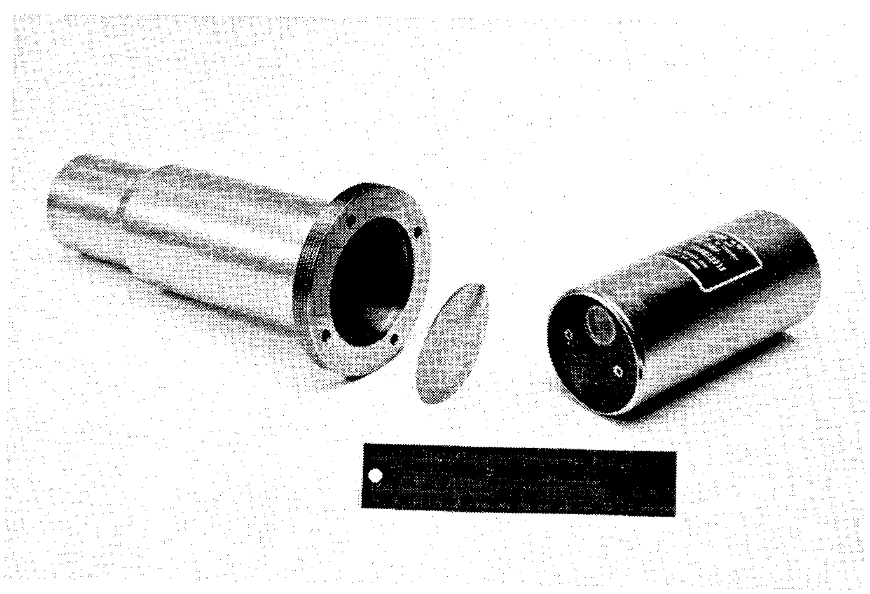

Figure 70: Fuzewell for FIGPB

5.9 Insensitive Munition Fuze Technology Explosive Train Tests

The IMFT program[13] produced an explosive train quite similar to the modified FMU-139 developed in this program. Figure 71 shows the salient features of this design. As it is not based on any existing fuze, this design had the freedom to package the explosive train differently and not be concerned with length constraints. The rear half of the IMFT nose fuze concept (referred to as the critical module) contains the explosive train and the time delay circuitry for post impact functioning. The front half, which was not developed in the IMFT program, will contain the electronic safe/arm, wind turbine power supply, and proximity sensor. The critical module explosive train is started with an exploding foil initiator (EFI or slapper detonator). The slapper detonator is adjacent to an HNS IV pellet which launches a very small flyer plate into the PBXN-7 lead which is in intimate contact with the PBX-9502 booster. The explosives in this fuze are sized nearly the same as the modified FMU-139 yet no flyer is needed between the lead and booster as they have no interfering metal to attenuate the shock front. Provisions for venting the explosives in a cook-off are built into the design and have been proven. The critical module has undergone a large sequence of functional and hazard tests under the auspices of the IMFT program. Some of these tests are outlined here.

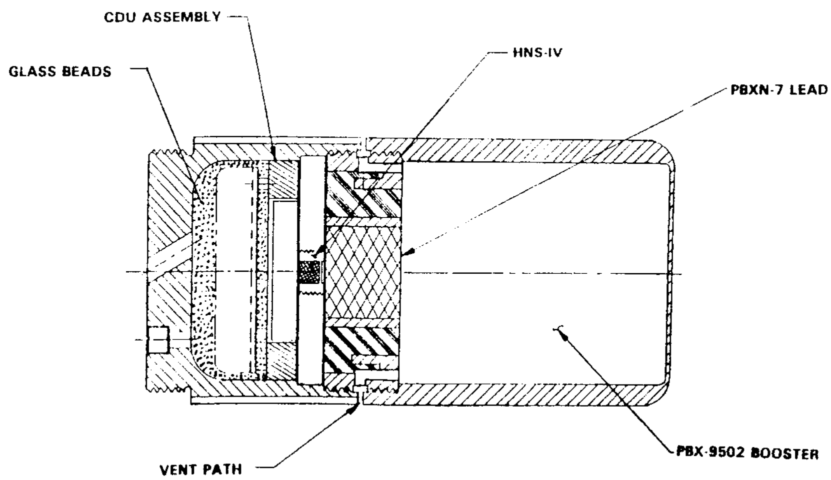

Figure 71: IMFT Critical Module

The critical module was tested against AFX-644 Low Wax version as summarized in Table XIII. The test unit was the forward half of a Mk-82 Bomb with a special flat bottom nose fuzewell and filled with only 70 lbs. of explosive. It was positioned above armor witness plate and instrumented with TOA pins. The entire explosive train from the high voltage slapper detonator to the AFX-644 was functioned in four tests. The first was at ambient conditions, the second at -51°F, the third at -54°F with AHM liner on the fuzewell, and the final shot was against a tritonal filled half bomb with the standard fuzewell with AHM and internal conduit. All shots were prompt detonations. The last shot was conducted to prove that this fuze could be used in a standard bomb if desired.

Section Six: All-up Round Hazards Testing

Within this report the term All-Up Round has a specific meaning. The storage of munitions is driven by safety issues. Missiles and cluster bombs are stored in an all-up state in that the entire round can be taken from storage to the aircraft with little or no maintenance/assembly action. General purpose bombs have to be built up from as many as twenty pieces such as fuzes and guidance kits. The major reason for this is that the hazard of the weapon from accidental fire or detonation is increased when the fuze is installed. The safe storage of an all-up general purpose bomb does not depend on the presence of the guidance kits or other ancillary pieces. The hazard testing reported in this section was accomplished in fuzed warheads without the ancillary pieces.

6.1 All-Up Round Fast Cook-off (Wood Bonfire) Test

A fast cook-off (wood bonfire) test was conducted on three All-Up Round (AUR) Mk-82 bombs containing AFX-644 Mod 0 and a modified FMU-139. The results of this test met the 1.2 Hazard Classification criteria prescribed by the United Nations.

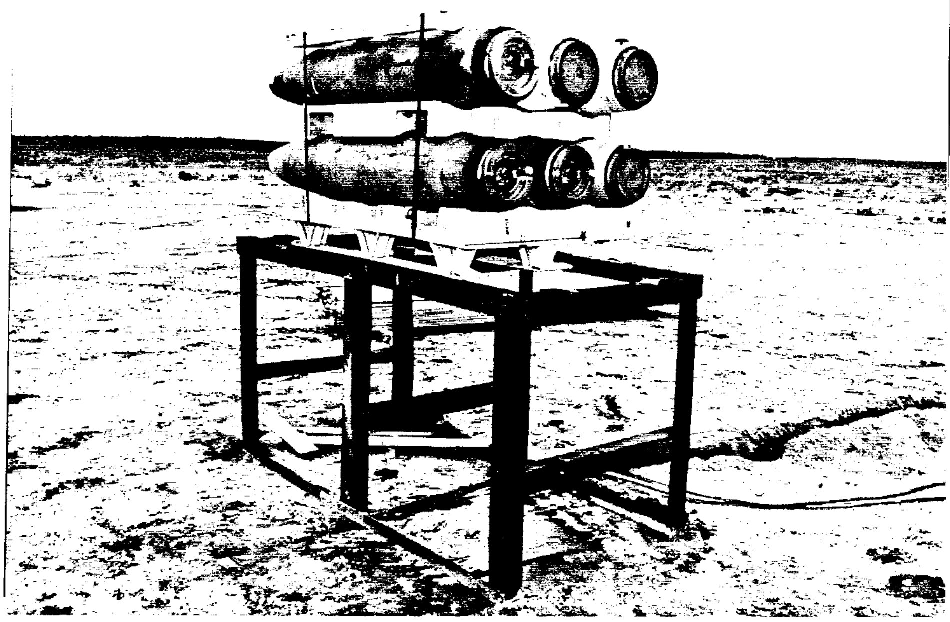

Figure 72: Three Bomb FIGPB Fuzed Fast Cook-off Test Set Up

The bombs were situated on a new standard metal pallet as shown in Figure 72. The bottom position of the center column (Item "S") and both positions of one of the outer columns (Top: Item "K", Bottom: Item "B") were filled with live, fully assembled bombs. The other positions in the pallet contained BDU-50s. Each of the live bombs was configured as a Fuzed Insensitive General Purpose Bomb (FIGPB), incorporating a modified aft closure, fuzewell and FMU-139 as previously described. The fuze was configured as it would be in storage with the Mk-8 lead in-line with the PBXN-7 'flyer plate' lead and the auxiliary PBX-9502 booster. The detonator was removed, simulating the out-of-line, storage condition. The fuze was held in the bomb with a retaining device. This L-shaped piece of steel was bolted to the modified aft closure using one of the three, threaded "tuff seal" injection ports. The L-shaped piece pressed a circular washer against the face plate of the fuze to hold it in place (Figure 73). This retaining clamp is not intended to replace a proper fuze locking ring but was 'jury rigged' for testing only. The pallet of bombs was placed on a steel stand approximately 1 meter above the ground. Thermocouples were placed in and around the test items. Planks of 1-inch x 4-inch lumber were placed under, around and above the pallet to a distance of approximately 1 meter. Approximately 20 gallons of diesel fuel were applied to the stack. The wood and fuel were ignited using thermite grenades.

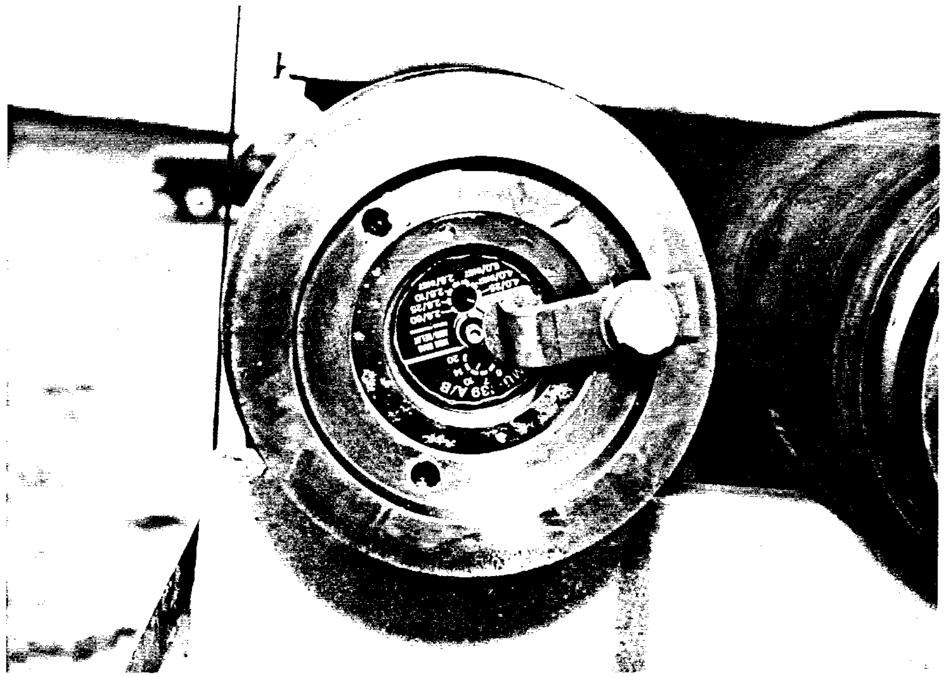

Figure 73: Close Up of FIGPB Modified Aft Closure and FMU-139

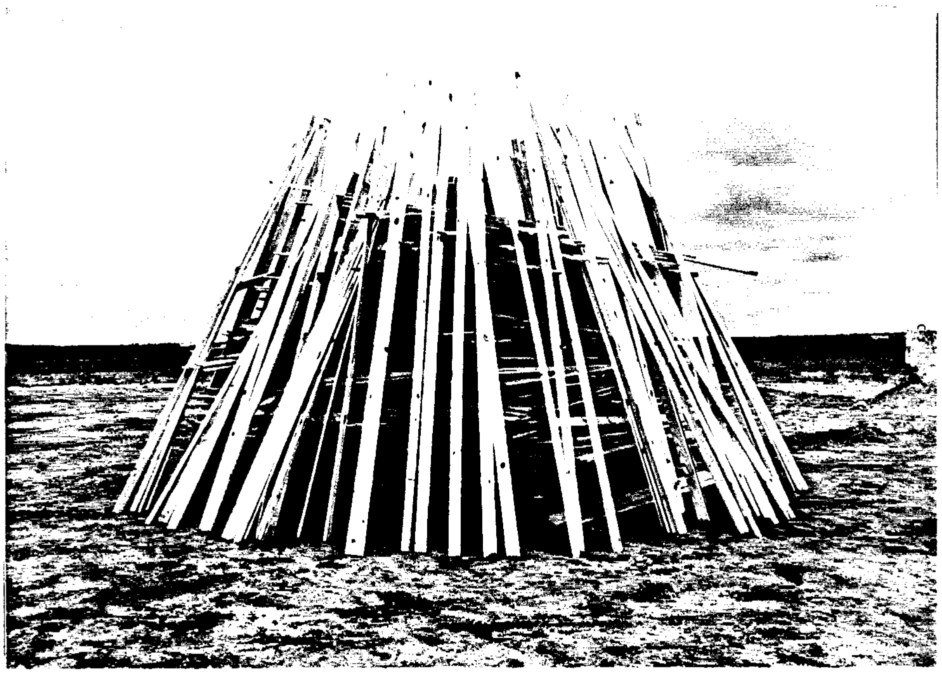

Figure 74: FIGPB Fast Cook-off Wood Bonfire Test

The fire burned for 8 minutes and 40 seconds before the first reaction occurred. The first item ("B") vented and left the test stand, coming to rest approximately 45 feet from its initial position (Figure

75). The final position was in the direction of the bomb tails, indicating a nose venting propelled the item from its initial position. The internal and external temperatures at the time of venting were 850-900°C. Item "B" remained stationary and intact after the initial venting. Subsequent burning of the explosive was evidenced by flames protruding from the orifices in the nose and tail. The recovered bomb case was filled with charred explosive residue which was also present outside this item near the nose and tail orifices. The fuze was expelled without reacting when the bomb vented and was subsequently recovered. The auxiliary booster was also recovered (Figure 76).

Figure 75: Item "B" from FIGPB Fast Cook-Off Test

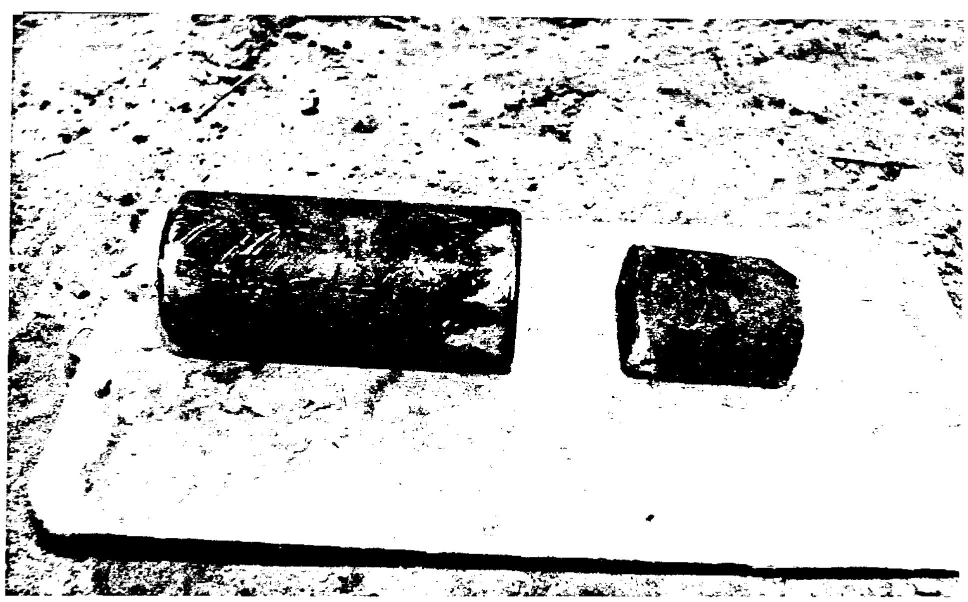

Figure 76: Fuze and Auxiliary Booster for Item "B" from FIGPB Fast Cook-Off Test

The second item ("S") reacted 12 minutes and 10 seconds after the fire started. The third item ("K") reacted 4 seconds later. Both items ruptured in response to the pressure build-up from reaction off-gases. The cases were split and aft closures, charging wells and fuze "plumbing" fixtures were expelled. Item "S" was recovered approximately 45 feet from the test stand in the direction of the bomb noses (Figure 77). Item "K" was recovered approximately 115 feet from the test stand in the direction of the bomb noses at a heading of approximately 45 degrees from the original position (Figure 78). Approximately 20 lb. of baseball-sized chunks of unreacted explosive were recovered from the area surrounding the test stand (Figure 79). The fuzes from both items "S" and "K" were recovered approximately 200 feet from the test stand. They remained inside the fuzewell liners after being expelled from the bombs with no evidence of reaction from either the PBXN-7 or PBX-9502 boosters (Figure 80).

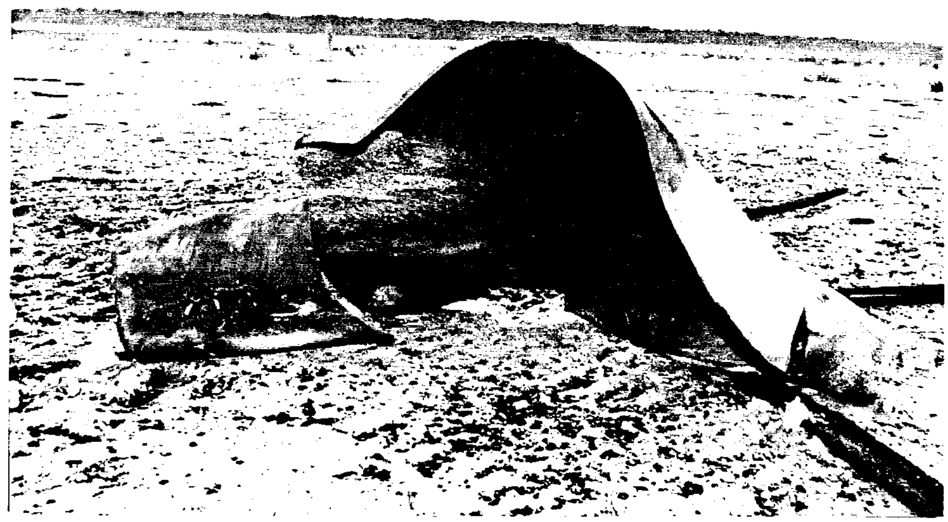

Figure 77: Item "S" from FIGPB Fast Cook-Off Test

Figure 78: Item "K" from FIGPB Fast Cook-Off Test

Figure 79: Raw AFX-644 High Explosive Recovered from FIGPB Fast Cook-Off Test

Figure 80: "B","K" and "S" Fuzes from FIGPB Fast Cook-Off Test

The United Nations criteria for assignment of articles to division 1.2 based upon bonfire testing state "if explosion of the total contents does not occur practically instantaneously, but...any metallic projection with mass exceeding 150 g is thrown more than 15 m from the edge of the stack, then the product, as packaged, is assigned to division 1.2." The results of this All-Up Round Mk-82 test met these criteria. Had all three bombs reacted as the first did, and had the explosive train in the fuzes contained only EIDS explosives, the results would meet the more stringent 1.6 hazard classification.

The pressure ruptures observed in this test appeared to be more violent than the mild venting observed for unfuzed Mk-82s containing baseline AFX-644. In the AUR configuration, one of the major vent paths is occupied by a fuze. Milder results could be obtained using an aft closure ring mechanism for the bomb as developed by Koontz, et. al at NAWC[17]. These closure devices had the ability to open the bomb more completely to allow better warhead venting. This improvement is recommended for any AUR bomb system which would enter full-scale production.

6.2 Insensitive Munition Fuze Technology Fast Cook-Off

The IMFT critical module had previously undergone fast cook-off tests as a bare fuze. Three of these tests were successfully conducted. The baseline AFX-644 loaded Mk-82 had also survived such a test by venting and burning out of both fuzewells. The combination of fuze and bomb had the potential to exhibit worse reaction as the venting for both warhead and fuze was restricted by the presence of the other. A single fuzed Mk-82 bomb was loosely strapped to a metal stand and surrounded by at least a meter of kerosene soaked wood (Figure 81). At seven minutes into the test, the bomb pressure ruptured. This pressure rupture was a result of off-gassing of the 4% polywax AFX-644 and was not a deflagration. A large quantity of explosive was recovered from the test and one piece of casing was thrown more than 100 feet. At approximately 15 minutes into the burn the wood pile had burned low enough to see that the most of the bomb remained on the stand (Figure 82) and was completely empty of explosive except for the fuze. At 22 minutes the critical module could be seen to vent very mildly for approximately five minutes with smoke and flame spouting from the bomb nose (Figure 83). Although the one fragment thrown was outside the 15 meter criterion for 1.6 hazard classification, the test easily met the 1.2 hazard classification criteria. Venting improvement to the warhead would surely allow the weapon to meet the 1.6 level. This test proved that the fuze does degrade the bomb's response to the fast cook-off test and that the fuze is less sensitive to this thermal stimuli than is the bomb.

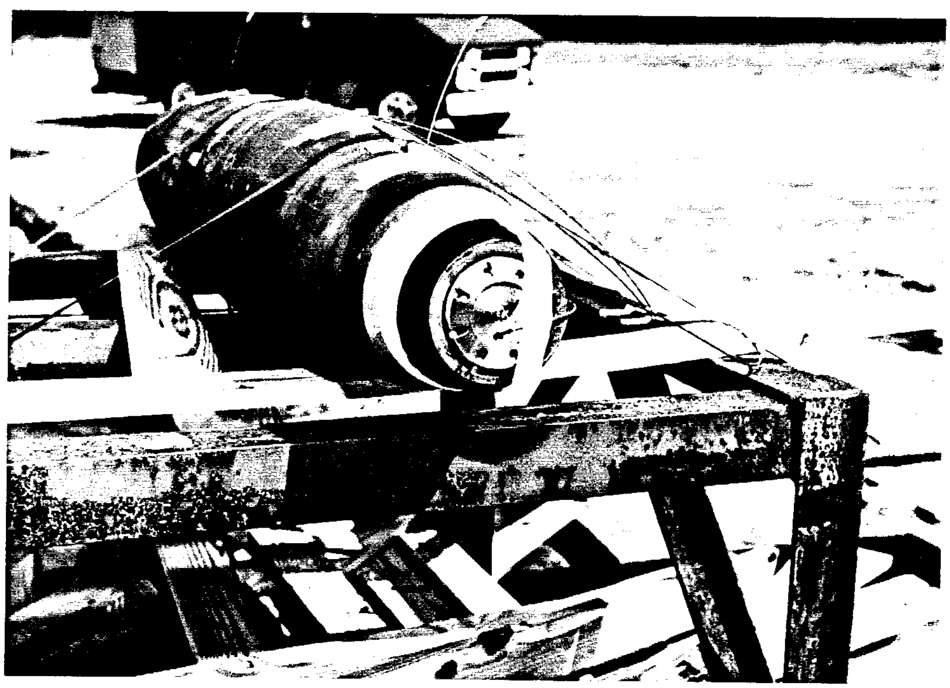

Figure 81: IMFT Fuzed Mk-82 Containing 4% Wax AFX-644 Fast Cook-Off Test Set Up

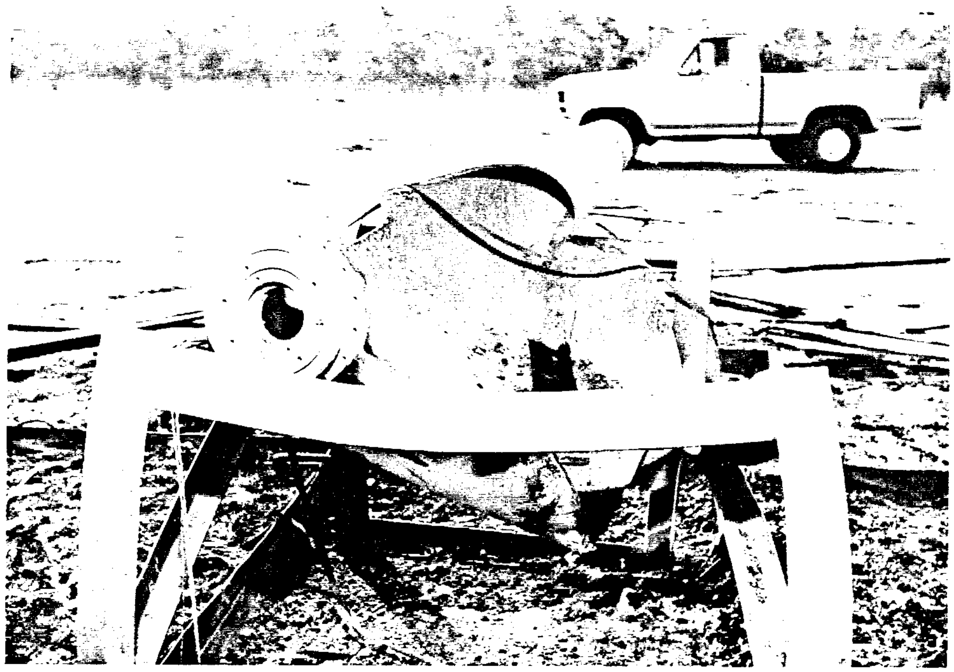

Figure 82: Split Mk-82 Bomb Casing from IMFT Fast Cook-Off Test

Figure 83: View of Burned out Critical Module from IMFT Fast Cook-Off Test

6.3 Insensitive Munition Fuze Technology Slow Cook-Off

As with the fast cook-off, both the fuze and the warhead had previously passed the slow cook-off test. By blocking the bomb's favorite vent path, the fuze could exacerbate the response to the test. A single nose-fuzed item was placed inside an aluminum oven as was explained in section 2.1. In both the previous tests the items vented from the nose fuzewell and burned in place, non-propulsively at an oven temperature of approximately 165°C with internal temperatures of 190°C. In this test, the tail fuzewell experienced a mild pressure rupture at 132°C which moved the bomb a few inches. At an oven temperature of 163°C the 4% polywax AFX-644 ignited and burned completely and non-propulsively out the tail fuzewell. The oven temperatures reached a plateau of 1122°C during the combustion of the AFX-644. Throughout this event the thermocouple inside the critical module peaked at 135°C which is well below the level at which reaction occurred in the slow cook-off tests of the fuze. The bomb case was intact following the test (Figure 84) as was the critical module in the nose fuzewell (Figure 85).

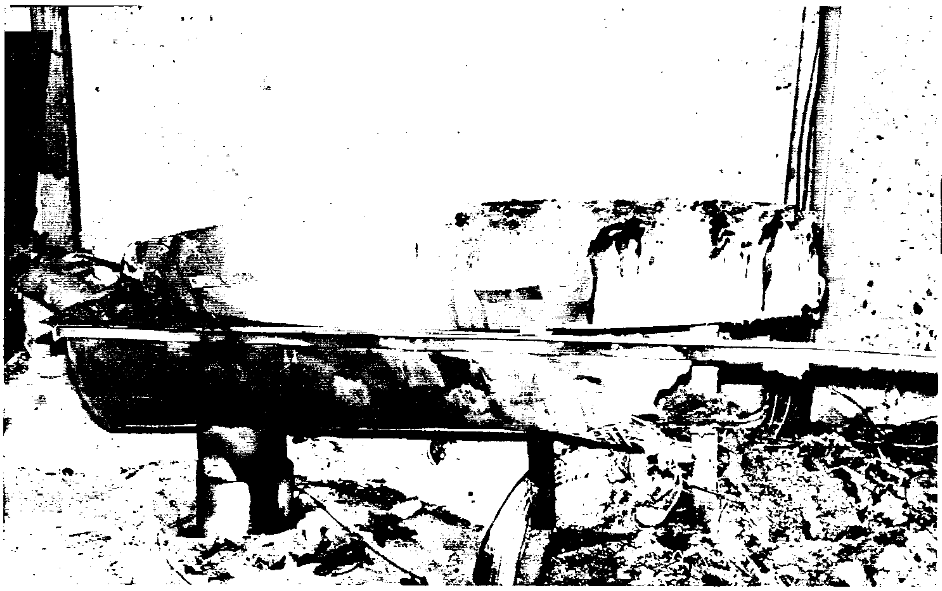

Figure 84: IMFT Fuzed Mk-82 Slow Cook-off Result

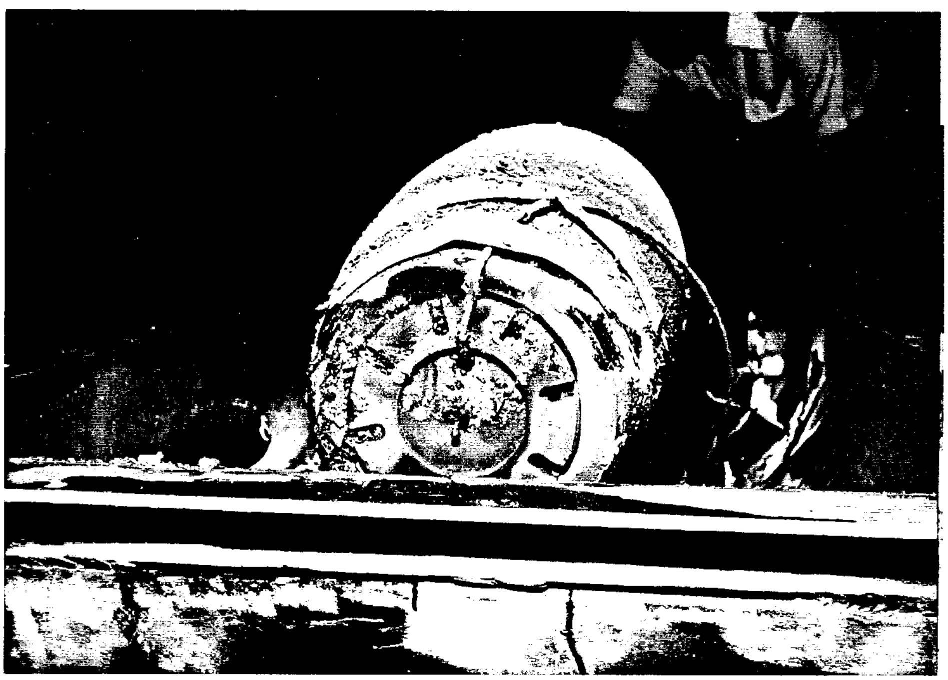

Figure 85: Critical Module from IMFT Fuzed Mk-82 Slow Cook-off Test

6.4 All-Up Round Sympathetic Detonation Test

An all-live, fuzed, full-scale (Mk-82) sympathetic detonation test of AFX-645 was conducted to demonstrate the survivability of this system as a fully assembled munition in a standard storage configuration. In this test all of the bombs were filled with AFX-645 and placed in the new standard metal pallet. All of the acceptor bombs contained prototype fuzes and auxiliary boosters. There was no evidence of detonation from four of the five acceptor bombs; however, the fifth item reacted violently or partially detonated after a substantial run-up.

The horizontal distance between the columns of bombs was approximately 0.88 inches. The vertical distance between rows was approximately 2.75 inches. The donor bomb was placed in the bottom, center position of the pallet. It had a net explosive weight (NEW) of 185.8 lb., resulting in a charge density of 1.62 g/cc (92.7 % TMD). The donor bomb was labeled as item "Z." The donor bomb was placed next to a bomb with a NEW of 180.5 lb. and a charge density of 1.61 g/cc (92.5% TMD). This adjacent bomb was labeled as item "T" and contained a modified FMU-139 tail fuze with Mk-8 lead, PBXN-7 lead and PBX-9502 auxiliary booster: the FIGPB tail fuze. The acceptor bomb on the other side of the donor bomb had a NEW of 184.2 lb. with a charge density of 1.63 g/cc (93.5% TMD). This bomb was labeled as item "A" and contained the nose fuze developed during the Insensitive Munitions Fuze Technology[13] (IMFT) program. This fuze is an intrinsically safe, in-line, slapper detonator system with an HNS IV pellet, PBXN-7 lead and a PBX-9502 booster. The acceptor bomb above the donor bomb, in the top, center position of the pallet had an explosive weight of 168.5 lbs. The charge density was 1.57 g/cc (90.2% TMD). This bomb was labeled as item "X" and contained the FIGPB tail fuze. The bomb above item "T" was labeled as item "&." It had an explosive weight of 180.5 lb. with a charge density of 1.60 g/cc (92.0% TMD). It also contained an FIGPB tail fuze. The bomb above item "A" was labeled as item "O." It had an explosive weight of 189.1 lb. with a charge density of 1.69 g/cc (96.9% TMD) and contained an IMFT nose fuze.

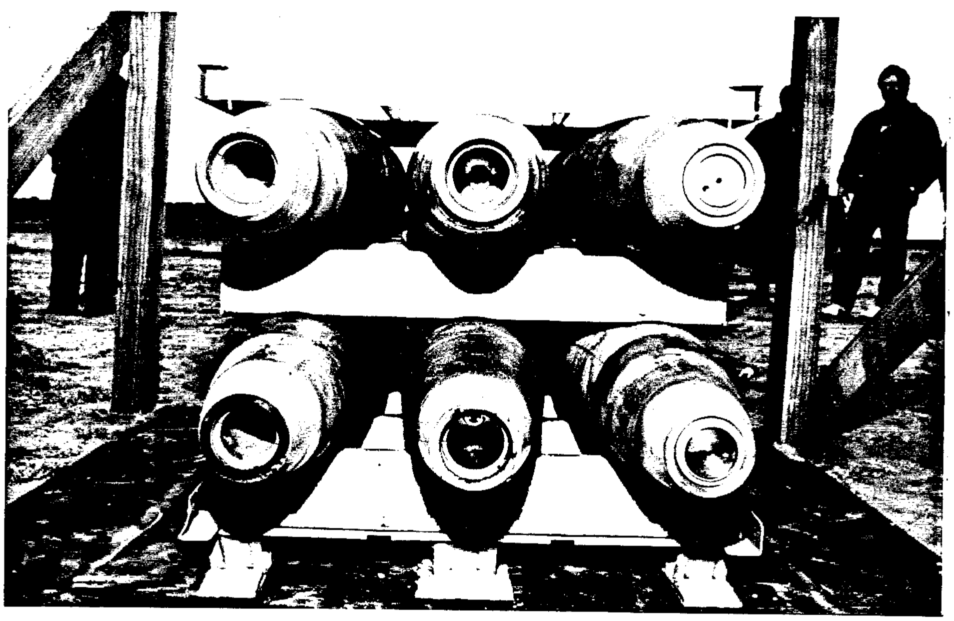

Figure 86: Nose View of All-up Round Sympathetic Detonation Test Set Up

The assembled pallet was positioned on a 6 ft x 6 ft x 1 in steel armor plate to obtain signatures from the donor fragments as well as any generated by the adjacent acceptor bombs. A 6 ft x 6 ft x 0.75 in witness plate was placed above the pallet at a height of 6 feet. It was covered with sandbags and supported on a wooden stand. Armor plates (12 ft x 12 ft x 0.75 in) were placed upright on both sides of the pallet at a distance of approximately 6 feet from the center of the pallet to obtain signatures from the acceptor bombs in the event of a detonation (Figures 86,87). Only a single 1 inch thick plate was available for use in this test. The donor bomb was initiated from the nose fuzewell using 2.5 lb. of C-4.

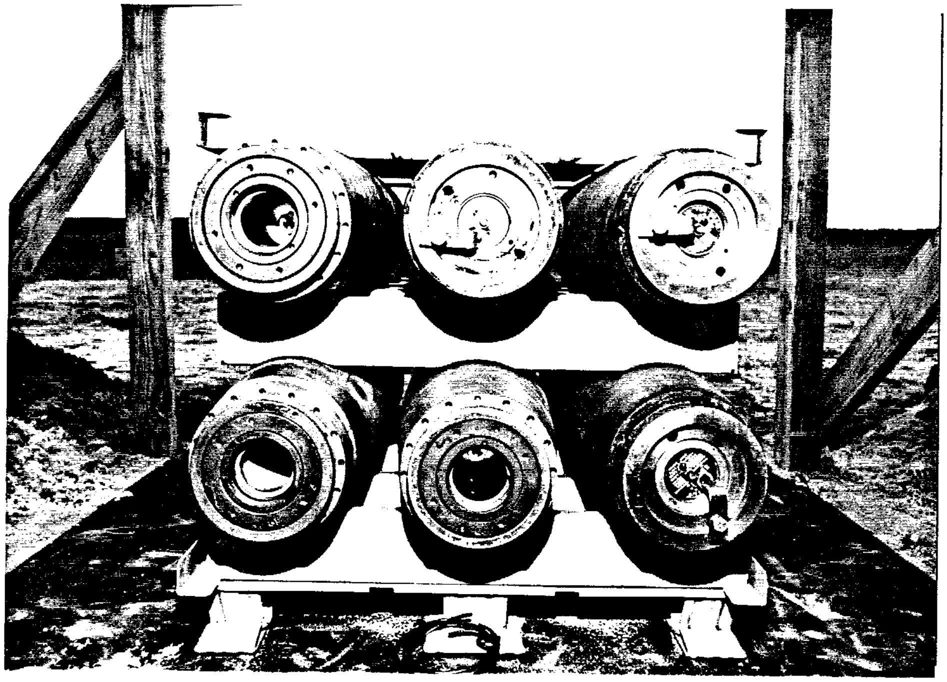

Figure 87: Tail View of All-up Round Sympathetic Detonation Test Set Up

The bottom witness plate was heavily scarred and cracked from the detonation of the donor bomb. The signature from the donor detonation was very symmetrical about the center point of the armor plate. Besides this donor scarring, a few fragment markings were observed beyond the original position of item "A" (Figure 88). They were isolated to the last 30-40 inches of plate in the region originally covered by the tails of the bombs. Both vertical plates were bent severely by the impact of the diagonally positioned acceptor bombs as they were accelerated by the detonation of the donor bomb. The scarring on the side witness plate closest to items "T" and "&" was minimal except for "peppering" from small donor fragments along with a few minor perforations (Figure 89). The lower region was coated with explosive residue. The plate was deformed (folded) with a crease at approximately 65 inches from the bottom of the plate. The side witness plate closest to items "O" and "A" was cracked into two pieces in the region corresponding to the crease on the other plate (Figure 90). The bottom section of the plate was scarred heavily in the region of the plate corresponding to the original tail position of item "A." The top section of the plate was scarred near the crack, but unscathed in the uppermost regions. The top witness plate was also fractured into two pieces due to the mechanical impact of the top center bomb as it was accelerated by the donor detonation (Figure 91). Also, there were a few impact markings and perforations of the top plate originally positioned above the tail region of items "O" and "A". It should be noted in these figures that substantially more witness plate damage than prior tests is evident because these plates were 0.75 inch thick instead of the standard 1.0 inch. Positively identifiable case remnants were recovered from all of the acceptor items. Specifically, the nose portion of item "A" was recovered along with another large, plate-like remnant (Figure 92). Also, a 3 ft x 0.5 ft piece of item "O" was recovered indicating no high order detonation of this item occurred (Figure 93). Large, plate-like pieces of all of the other items were recovered as well (Figures 94-96). None of the fuzes were recovered.

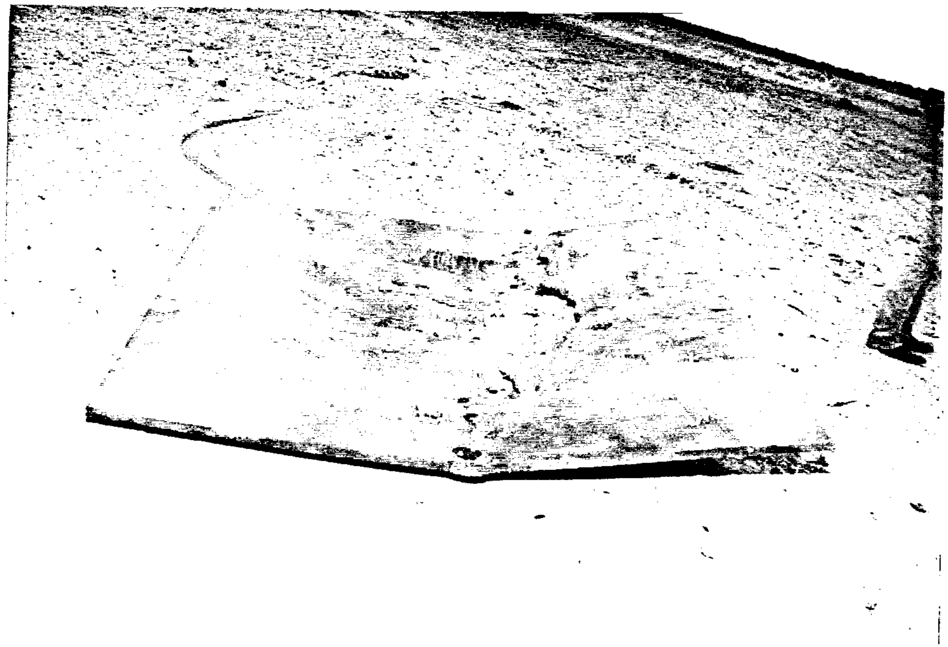

Figure 88: Bottom Witness Plate from All-up Round Sympathetic Detonation Test

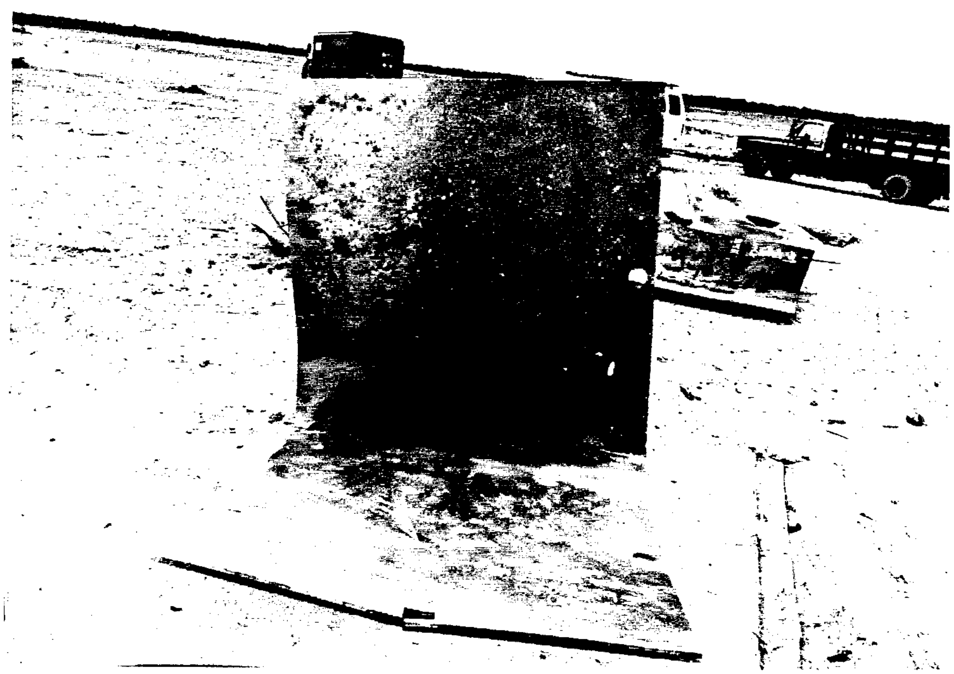

Figure 89: FIGPB Fuzed Side Witness Plate from All-up Round Sympathetic Detonation Test

Figure 90: IMFT Fuzed Side Witness Plate from All-up Round Sympathetic Detonation Test

Figure 91: Top Witness Plate from All-up Round Sympathetic Detonation Test

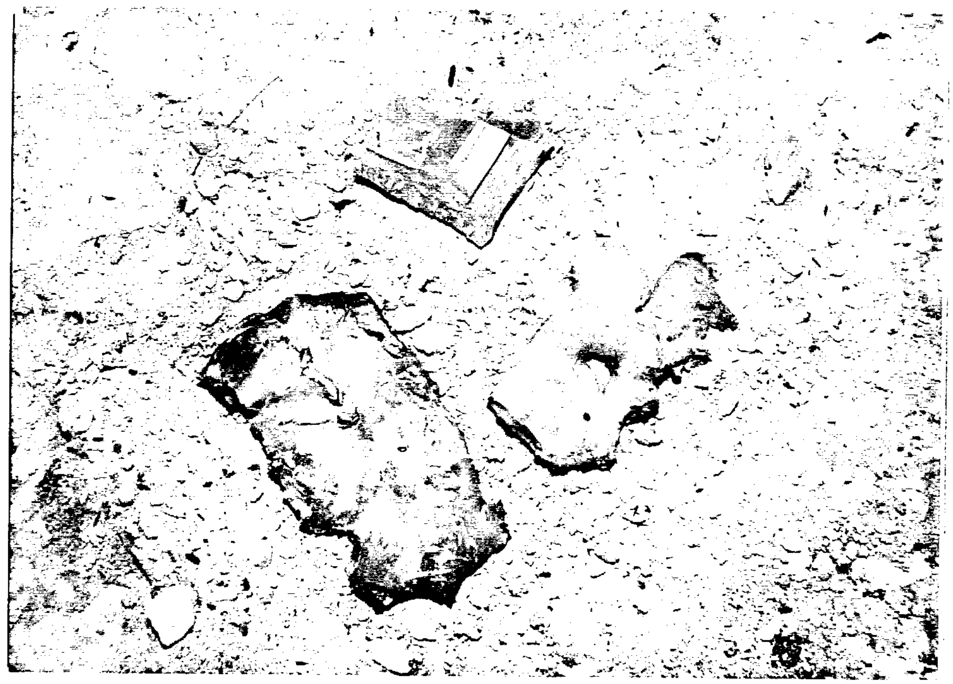

Figure 92: Item "A" Pieces from All-up Round Sympathetic Detonation Test

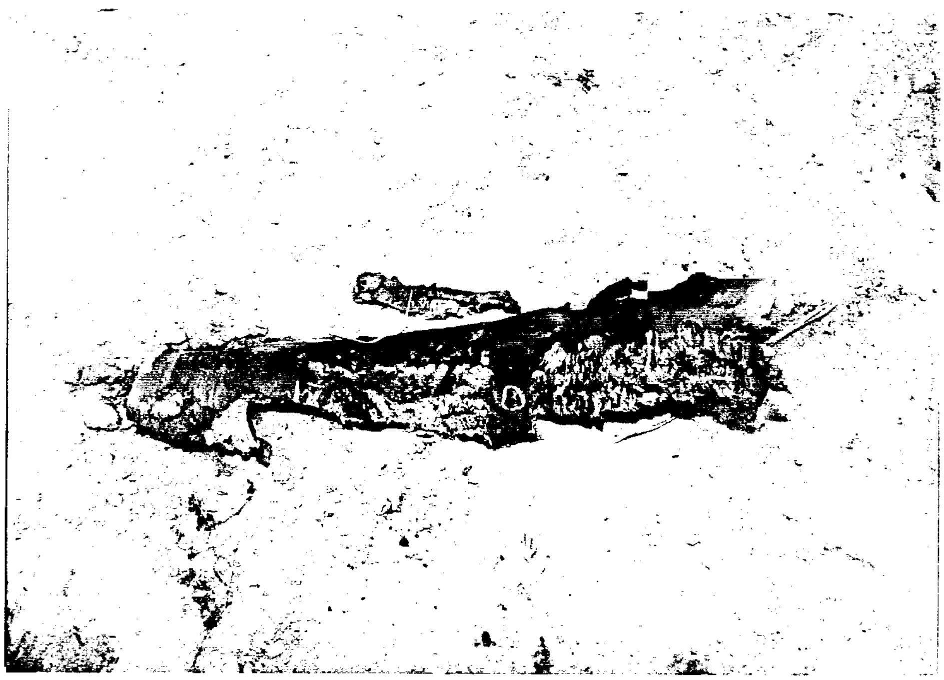

Figure 93: Item "O" Pieces from All-up Round Sympathetic Detonation Test

Figure 94: Item "T" Pieces from All-up Round Sympathetic Detonation Test

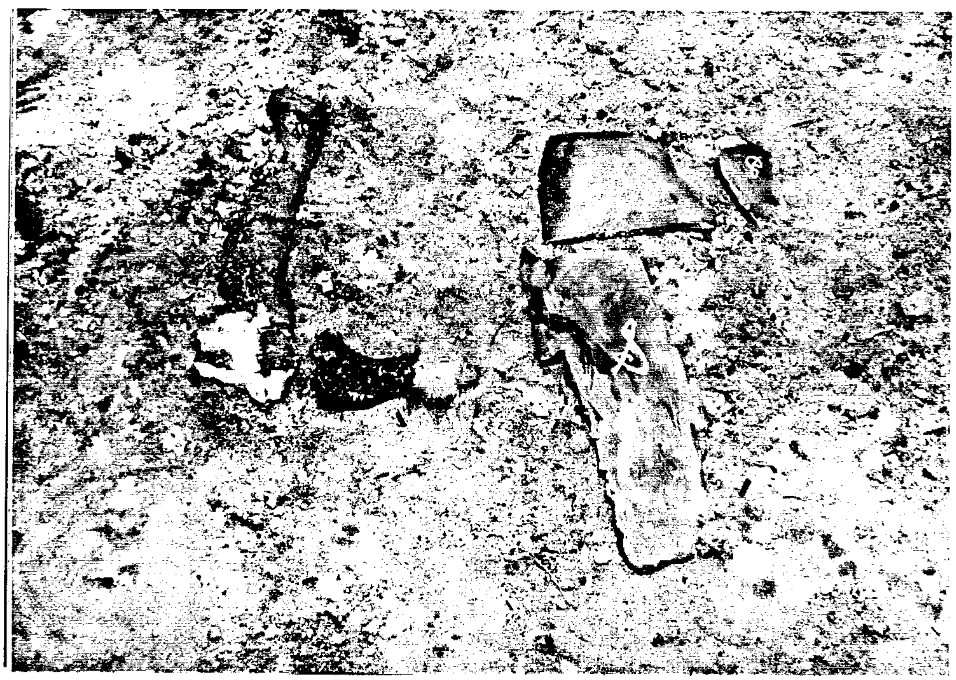

Figure 95: Item "&" Pieces from All-up Round Sympathetic Detonation Test

Figure 96: Item "X" Pieces from All-up Round Sympathetic Detonation Test

The results of this test were essentially identical to those reported for the unfuzed, all-live, sympathetic detonation test of Mk-82s containing AFX-645. The evidence from this test reveals that four of the five acceptors in this test did not propagate the detonation of the donor bomb. These included both of the diagonally positioned items. One of the items adjacent to the donor bomb ("A") did result in a non-prompt, violent reaction or a partial detonation. However, the energy emitted by this reaction was not substantial enough (or prompt enough) to propagate a reaction in its nearest neighbor bomb, item "O" (which was also originally positioned diagonally with respect to the donor bomb). Most significantly, the presence of the fuzes did not exacerbate the reaction of the acceptor bombs including item "A" which, based on the case remnants, was not initiated by the IMFT fuze it contained, but in a delayed response to the impact of the donor bomb.

Section Seven: Conclusions

General

The objectives of this technology demonstration program have been achieved. Full scale testing results for AFX-644 and subsequently AFX-645 have demonstrated the feasibility of fielding a Mk-82 bomb with a hazard classification of 1.6 and a fully assembled Mk-82 bomb with a 1.2 hazard classification. Minor modifications to existing fuzes can allow reliable initiation of insensitive high explosives without degrading the response to hazardous stimuli. Although the blast/fragmentation performance of the system is slightly less than that of tritonal filled bombs, the effectiveness in terms of single shot probability of kill should be unchanged especially if used in a precision strike manner. The operational and safety benefits of an all-up round system derived from larger quantity per distance allowances and minimal build-up activities will far out-weigh the small loss in performance. The technologies developed in this program are ready for transition into the next generation of munition systems.

Insensitive High Explosive Development

AFX-645 is a melt castable formulation which could be easily processed in existing high-rate loading facilities. It employs a well specified grade of nitrotriazolone (NTO), and other components for which detailed material specifications already exist. The AFX-645 wax/surfactant system is suitable for use in military environments. When compared with the conventional D2 wax system, the I-800/Ganex mix in AFX-645 minimizes exudation and off-gassing and enhances the TNT/wax emulsion characteristics. It also dramatically effects the shock sensitivity, critical diameter and energy of the aluminized TNT/NTO formulation. AFX-645 was developed by balancing energy and sensitivity requirements for surviving sympathetic detonation in the new standard metal pallet. AFX-645 blast performance measured in Mk-82s approaches that derived from tritonal filled Mk-82s.

The baseline formulation for AFX-644 achieved the UN criteria for extremely insensitive detonating substances (EIDS) and insensitive article test requirements for fast cook-off, slow cook-off and bullet impact testing. AFX-645 is less sensitive in shock and does not propagate the detonation of nearest neighbor donor bombs in a sympathetic detonation test. The new pallet for Mk-82 bombs introduced to the USAF independently of this program has shifted the most vulnerable position for sympathetic detonation from the diagonal acceptor to the adjacent acceptor. The cook-off response of baseline AFX-644 and low wax AFX-644 was mild. Based on this evidence and the similarity in formulations, AFX-645 is very likely to meet EIDS and 1.6 hazard classification criteria.

Fuze Development

The baseline AFX-644 formulation had a critical diameter approaching 40mm and cannot be initiated by the standard FMU-139 fuze. AFX-644 Mod 0 has a critical diameter approaching 50mm. The critical diameter of AFX-645 is estimated to be 40mm and it is less sensitive than baseline AFX-644. A 2.44 inch diameter, 3.0 inch long booster of PBX-9502 can detonate baseline and AFX-644 Mod 0. AFX-645 is between these two in gap test results. Thus by interpolation, it too can be detonated by this booster at service conditions.

A cylinder of PBX-9502 was selected as the auxiliary booster configuration due to its ease of fabrication. Hydrocode calculations show that a smaller booster is feasible if the shape is changed to a hemisphere. A domed booster can be designed such that its curvature approaches that of the advancing detonation front for an efficient transfer of energy. A domed fuzewell is also stronger than the cylindrical fuzewell used in this program. The material savings with the domed design may be larger than the extra fabrication cost.

The detonator and small lead in the FMU-139 can be easily augmented with a PBXN-7 booster to launch a small flyer plate capable of detonating the large PBX-9502 auxiliary booster. This concept is tolerant to dimensional inaccuracy in assembly. The electrical connector for the FMU-139 can be relocated to the fuze face-plate. This is required to employ a cylindrical (vs. toroidal) booster. The relocated electrical connector allows the charging tube to be moved to the aft closure of the bomb which has several advantages: it simplifies explosive loading procedures as the fuzewell can be inserted after filling; the flat bottomed fuzewell provides for better shock matching between the booster and main charge; and the blind cavity provided by the fuzewell could be used as the storage can for the fuze as it is easily hermetically sealed. This last feature is a key element in achieving an all-up round general purpose bomb.

All-up Round Demonstration

Alterations of the Mk-82 to accommodate AFX-645, a re-configured fuzewell and modified FMU-139, are modest. The new design facilitates loading in high-rate production facilities. Hazards testing of both fuzed and un-fuzed modified Mk-82s has been accomplished. In an unfuzed state, baseline AFX-644 bombs have met all criteria for EIDS and 1.6 hazard classification except for the sympathetic detonation test. AFX-645 was not put through the gauntlet of prior tests but does pass the sympathetic detonation criteria. There is no reason to believe it would not pass the other insensitivity tests equally well as the baseline formulation.

In a fuzed state, a 4% polywax version of AFX-644 has passed the slow cook-off test to the 1.6 hazard classification criteria and the fast cook-off to the 1.2 hazard classification level. Fuzed Mk-82 bombs loaded with AFX-645 have passed fast cook-off to the 1.2 level and have passed the sympathetic detonation test. Better bomb case venting would allow the fuzed bomb to meet the 1.6 hazard classification criteria.

Final Summary

Baseline AFX-644, an insensitive high explosive for general purpose bombs, has been tailored to provide a qualifiable explosive designated AFX-645. This new formulation eliminates the poor processing characteristics of baseline AFX-644 and improves upon the performance of AFX-644 Mod 0. AFX-645 provides the proper balance of insensitivity, performance and initiability required for safe storage, safe handling, reliability and lethality in operational environments.

AFX-645 has been successfully integrated with a Mk-82 bomb and a fuze system derived from the FMU-139. The fuzed insensitive general purpose bomb (FIGPB) system integrates an insensitive booster, allowing fully assembled munitions to be safely stored and transported.

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